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GLOBAL UNCERTAINTY ANALYSIS OF FULL-SCALE SUBMARINE PROPULSION PREDICTIONS USING TOW-TANK MODEL TESTS

by

F. Noblesse
J.R. Lee
M.R. Pfeifer
R.B. Hurwitz

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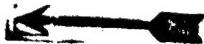
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ABSTRACT

Estimates of the uncertainties attached to full-scale predictions of submarine resistance and propulsion based on standard submarine tow-tank model tests are obtained by means of a global uncertainty analysis. The analysis takes into account all the component uncertainties, including the uncertainties associated with the prediction procedure and the measurements performed both at model scale and at full scale, which influence the overall uncertainty of full-scale predictions.

ADMINISTRATIVE INFORMATION

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INTRODUCTION

Estimates of the uncertainties attached to full-scale predictions of submarine resistance and propulsion based on standard submarine tow-tank model tests are obtained in this study by means of a global uncertainty analysis. The analysis takes into account the uncertainties associated with the prediction procedure and the uncertainties of measurements performed both at model scale and at full scale. Thus, the uncertainty analysis developed in the study takes into account all the component uncertainties which influence the overall uncertainty of full-scale predictions.

The prediction procedure, summarized in Appendix A, entails both resistance and propulsion tests. Five primary model-scale variables are measured in these model-scale tests. These measured primary model-scale variables are the carriage speed and the drag, which are measured in both resistance and propulsion tests, and the propeller rpm, thrust, and torque measured in propulsion tests.

The five measured primary model-scale variables are used to determine several "transformed" model-scale variables via analytical relations. These relations are given in Appendix A. The transformed model-scale variables include the residuary-drag coefficient, determined in resistance tests, and four nondimensional variables obtained via propulsion tests : the total-drag coefficient, the advance ratio, the thrust-deduction factor, and the propulsive efficiency.

The curves representing the advance ratio, the thrust-deduction factor, and the propulsive efficiency as functions of the total-drag coefficient are fundamental elements of the model-scale to full-scale extrapolation. The relations used in this extrapolation are given in Appendix A. The extrapolation procedure is usually implemented for a specified full-scale speed or for a specified full-scale shaft horsepower. Both cases are examined in the global uncertainty analysis developed in the study. Three other cases, in which full-scale predictions are obtained for a specified value of the propeller rpm, thrust, or torque, are also examined for completeness.

The uncertainty analysis, based on classical expressions for the errors [1] and elementary differential calculus, is expounded in Appendix B. The Fortran-code implementation of the expressions for the uncertainties obtained in Appendix B is given in Appendix C. Example input and output files associated with the Fortran-code are also included in Appendix C. The global uncertainty analysis developed in Appendices B and C provides a practical tool for estimating the uncertainties of full-scale predictions in terms of component uncertainties attached to model-scale and full-scale measurements.

Full-scale theoretical predictions are ultimately compared to values measured in full-scale trials. The observed differences between the full-scale measurements and the full-scale values predicted using model-scale tests are usually expressed in the form of a correlation allowance in the relation defining the drag coefficient.

The correlation allowance accounts for aspects of the full-scale flow, such as the hull roughness, that cannot be accounted for in model tests. The correlation allowance also accounts for other limitations of the model-test to full-scale prediction procedure, notably errors that are systematically introduced into the predictions due to limitations inherent to the prediction procedure. Thus, systematic errors associated with the characteristics of the tow-tank and the experimental set-up used in the implementation of the prediction procedure are largely included in the correlation allowance, as is attested by the fact that different correlation allowances are used for different tow-tanks.

Thus, the correlation allowance largely accounts for the systematic (bias) errors associated with the effects of the tank bottom and walls, the influence of the strut holding the model, the strain gauges, and the electronic equipment. Therefore, as long as no significant changes are made in the characteristics of the tow-tank, the strut, the strain gauges, the electronic equipment, and the testing procedure, systematic errors attached to these aspects of the prediction procedure can largely be ignored in the uncertainty analysis (since they are already included in the correlation allowance to a large extent, as was noted previously).

Errors stemming from residual waves in the tank and differences between full-scale and model-scale depth of submergence can also be ignored in the uncertainty analysis to a large extent, although these errors are likely to vary with the design speed, and thus cannot be completely ignored in the uncertainty analysis. Additional systematic errors due to geometrical imprecisions of the model clearly are model-dependent, and thus cannot in principle be ignored in the uncertainty analysis.

In summary, it is proper to ignore most systematic (bias) errors in an uncertainty analysis of a consistent prediction procedure because these consistent errors are largely included in the correlation allowance attached to the prediction procedure. This general consideration and consideration of the substantial

difficulties involved in obtaining reliable estimates of bias errors --- more precisely, of the effects of the bias errors that are not already included in the correlation allowance --- suggest that a reasonable practical way of accounting for bias errors is to simply increase the precision (random) errors by means of a multiplicative factor. Specifically, the bias errors of the measured primary model-scale variables are taken equal to the precision errors of these variables in the analysis considered further on. This practical approach is justified by the extreme complexities, and uncertainties, involved in obtaining realistic estimates of the influence of the bias errors that are not already included in the correlation allowance upon full-scale prediction uncertainties.

The precision errors attached to the measured primary model-scale variables are determined via a statistical analysis of the repeatability of model-scale measurements. This repeatability analysis is presented in Appendix D.

Results of the repeatability analysis presented in Appendix D and of the global uncertainty analysis expounded in Appendix B are presented below for several cases, with the purpose of analyzing the contribution of the major component uncertainties which influence the overall uncertainty of full-scale predictions.

RESULTS OF UNCERTAINTY ANALYSIS

The uncertainty analysis developed in the study is applied to a typical case, which is defined below (and in the input file listed in Appendix C). The identifying numbers of the model, the propeller, and the resistance (EHP) and propulsion (SHP) tests corresponding to the case considered here are

model no.	propeller no.	EHP exp. no.	SHP exp. no.
XXXX	XXXX	XXX	XXX

The tank-water density and viscosity are

density	viscosity
1.937 slug/ft ³	1.084X10 ⁻⁵ ft ² /sec

The length and the wetted-surface area of the model, and the diameter of the propeller are

length	area	prop diameter
22.697 ft	138.179 ft ²	0.9986 ft

The carriage speed and the drag in the resistance (EHP) tests are

speed	drag
6.0 knots	46.66 lbs

The carriage speed, the propeller rpm, the total drag R_T , the tow force ΔR , and the propeller thrust and torque in the propulsion tests are

speed	rpm	drag	tow force	thrust	torque
18.0 knots	923.4	392.64 lbs	70.1 lbs	551.0 lbs	1501.0 in-lbs

The slopes of the curves representing the advance ratio, the thrust-deduction factor, and the propulsive efficiency as functions of the total-drag coefficient are respectively equal to

advance ratio	thrust-deduction factor	propulsive efficiency
-0.249	0.067	-0.015

The length and the speed of the full-scale submarine are taken as

length	speed
380 ft	25 knots

Finally, the viscosity of sea-water is assumed equal to $1.282 \times 10^{-5} \text{ ft}^2/\text{sec}$.

As was already noted, results of the repeatability analysis presented in Appendix D and of the global uncertainty analysis expounded in Appendices B and C are presented for several cases for the purpose of analyzing the contribution of the major component uncertainties which influence the overall uncertainty of full-scale predictions.

Case M1 : contribution of precision uncertainties of model-scale measurements

It is instructive to begin by considering the full-scale prediction-uncertainties for the case when only the uncertainties that directly stem from model tests are taken into account. In this case, called M1 hereafter, the correlation allowance and full-scale conditions (i.e. the density and the viscosity of sea water, the geometry of the full-scale ship and propeller, the full-scale values of the speed, the propeller rpm, the thrust, the torque, and the shaft horsepower) are presumed known without uncertainty. The density and the viscosity of tank water, the length and the wetted-surface area of the model, and the propeller diameter are also presumed known without uncertainty in case M1. Furthermore, model-scale uncertainties are taken equal to the precision (random) errors determined in Appendix D. Thus, bias errors attached to the measured primary model-scale variables are not taken into account in case M1. Case M1 corresponds to a comparison of successive model tests within a series of consecutive tests.

The analysis of the repeatability of measurements of the five primary model-scale variables for standard submarine model testing given in Appendix D shows that relative precision uncertainties in resistance (EHP) tests are approximately equal to 0.15% for the carriage speed and 1.2% for the drag. These uncertainties are indicated in the following table :

Precision uncertainties of model-scale measurements in EHP tests

speed	drag
0.15%	1.2%

Appendix D indicates that the relative precision uncertainties in propulsion (SHP) tests are approximately equal to 0.15% for the carriage speed, 0.3% for the propeller rpm, 1.2% for the drag R_t and the tow force ΔR , and 0.5% for both the propeller thrust and torque. These uncertainties are listed below :

Precision uncertainties of model-scale measurements in SHP tests

speed	rpm	drag	tow force	thrust	torque
0.15%	0.3%	1.2%	1.2%	0.5%	0.5%

The analysis and the Fortran-code given in Appendices B and C show that the model-scale measurement uncertainties defined above yield a relative uncertainty of the residuary-resistance coefficient C_R approximately equal to 6%. The prediction-uncertainties Uspeed, Urpm, Uthrust, Utorque, USHP and UEHP for the full-scale speed, rpm, thrust, torque, SHP and EHP associated with the previously-defined model-scale uncertainties are listed in the next table for five cases, corresponding to rows number 2 to 6 of the table. These five cases correspond to predictions for a specified value of the full-scale speed, rpm, thrust, torque, or SHP.

Full-scale prediction-uncertainties for case M1

at given	Uspeed	Urpm	Uthrust	Utorque	USHP	UEHP
speed	n/a	0.35%	2.2%	2.25%	2.2%	1.55%
rpm	0.35%	n/a	2.3%	2.4%	2.4%	1.8%
thrust	1.15%	1.2%	n/a	2.25%	2.95%	2.5%
torque	1.15%	1.25%	2.25%	n/a	1.25%	0.95%
SHP	0.75%	0.85%	1.95%	0.85%	n/a	1.6%

The prediction-uncertainties given in the second and third rows, which respectively correspond to predictions for given full-scale values of the speed or the rpm, of the foregoing table are nearly identical. The prediction-uncertainties given in the bottom row of the table, corresponding to predictions for a given full-scale value of the shaft horsepower, are on the whole somewhat smaller than the prediction-uncertainties listed in the other rows.

The prediction-uncertainties listed in the foregoing table represent the contribution of precision errors of model-scale measurements when all other sources of errors (including bias errors of model-scale measurements, uncertainties of the density and the viscosity of tank water, and model-scale geometrical inaccuracies) are ignored. As was already noted, this table of prediction-uncertainties corresponds to a comparison of successive model tests within a series of consecutive tests. The contribution of uncertainties of the density and the viscosity of tank water, the model length and wetted-surface area, and the propeller diameter, are considered in case M2; and the sensitivity of prediction-uncertainties to model-scale bias errors is considered in case M3.

Case M2 : contribution of uncertainties of tank-water properties and model-scale geometry

The uncertainties of the density and the viscosity of tank water, the model length and wetted-surface area, and the propeller diameter are taken as is indicated below.

Uncertainties of tank-water properties and model-scale geometry

density	viscosity	length	area	prop diameter
0.1%	1.5%	0.1%	0.5%	0.05%

The prediction-uncertainties Uspeed, Urpm, Uthrust, Utorque, USHP and UEHP for the full-scale speed, rpm, thrust, torque, SHP and EHP associated with the uncertainties of model-scale measurements defined in case M1 and the uncertainties of tank-water properties and model-scale geometry now considered are listed in the next table for five cases corresponding to predictions for a specified value of the full-scale speed, rpm, thrust, torque, or SHP , as for case M1.

Full-scale prediction-uncertainties for case M2

at given	Uspeed	Urpm	Uthrust	Utorque	USHP	UEHP
speed	n/a	0.35%	2.3%	2.35%	2.3%	1.65%
rpm	0.35%	n/a	2.4%	2.5%	2.5%	1.95%
thrust	1.2%	1.25%	n/a	2.25%	3.0%	2.55%
torque	1.2%	1.3%	2.25%	n/a	1.3%	1.0%
SHP	0.8%	0.85%	1.95%	0.85%	n/a	1.6%

These uncertainties are not significantly larger than those obtained for case M1. Thus, the uncertainties of the density and the viscosity of tank water, of the length and the wetted-surface area of the model, and of the diameter of the propeller are sufficiently small that they have insignificant effect upon the prediction-uncertainties.

Case M3 : contribution of model-scale precision and bias uncertainties

As in cases M1 and M2, only the contribution of model-scale uncertainties are considered in case M3. Thus, the correlation allowance and full-scale conditions (i.e. the density and the viscosity of sea water, the geometry of the full-scale ship and propeller, the full-scale values of the speed, the propeller rpm, the thrust, the torque, and the shaft horsepower) are again presumed known without uncertainty for the case M3 now considered.

As was already noted in the introduction, model-scale bias errors are taken equal to the model-scale precision errors determined in Appendix D and listed previously for cases M1 and M2. The total (precision + bias) model-scale uncertainties which are considered in case M3 are then equal to $2^{1/2}$ times the uncertainties considered in cases M1 and M2.

The prediction-uncertainties Uspeed, Urpm, Uthrust, Utorque, USHP and UEHP for the full-scale speed, rpm, thrust, torque, SHP and EHP associated with the previously-defined model-scale uncertainties are listed in the next table for five cases corresponding to predictions for a specified value of the full-scale speed, rpm, thrust, torque or SHP , as for cases M1 and M2. This table indicates that the prediction-uncertainties for case M3 are equal to $2^{1/2}$ times the prediction-uncertainties for case M2, as one expects.

Full-scale prediction-uncertainties for case M3

at given	Uspeed	Urpm	Uthrust	Utorque	USHP	UEHP
speed	n/a	0.45%	3.25%	3.3%	3.3%	2.35%
rpm	0.45%	n/a	3.35%	3.55%	3.55%	2.75%
thrust	1.7%	1.75%	n/a	3.2%	4.25%	3.6%
torque	1.7%	1.85%	3.2%	n/a	1.85%	1.4%
SHP	1.1%	1.2%	2.8%	1.2%	n/a	2.25%

The prediction-uncertainties for case M3 may be regarded as the uncertainties of the full-scale predictions obtained using standard submarine model testing in the tow-tank for a specified full-scale submarine and propeller geometry and specified full-scale conditions. However, comparison of full-scale predictions to measurements in full-scale trials introduces additional uncertainties. These additional uncertainties, called full-scale uncertainties hereafter, stem from the uncertainties in the values of the density and the viscosity of sea water, the geometry of the full-scale ship and propeller, and the values of the full-scale speed, propeller rpm, thrust, torque, and shaft horsepower. The contribution of these full-scale uncertainties to the prediction-uncertainties is considered in case F.

Case F : contribution of full-scale uncertainties

All model-scale uncertainties are ignored in case F, which only considers the contribution of full-scale uncertainties. Thus, all model-scale variables, and the correlation allowance, are presumed known without uncertainty in case F.

The relative uncertainties of the density and the viscosity of sea water, of the length and the wetted-surface area of the full-scale submarine, and of the propeller diameter are taken as is indicated in the following table :

Uncertainties of full-scale input variables

density	viscosity	length	area	prop diameter
1%	2%	0.5%	1%	0.1%

The uncertainties of full-scale measurements are considered in Appendix E . The total (precision + bias) uncertainties of full-scale measurements are taken as

Uncertainties of full-scale measurements

speed	rpm	thrust	torque	SHP
0.6%	0.4%	3.0%	0.9%	0.9%

hereafter.

The prediction-uncertainties Uspeed, Urpm, Uthrust, Utorque, USHP and UEHP for the full-scale speed, rpm, thrust, torque, SHP and EHP associated with the foregoing full-scale uncertainties are listed in the next table for five cases corresponding to predictions for a specified value of the full-scale speed, rpm, thrust, torque or SHP .

Full-scale prediction-uncertainties for case F

at given	Uspeed	Urpm	Uthrust	Utorque	USHP	UEHP
speed	0.6%	0.75%	3.5%	2.05%	2.45%	2.25%
rpm	0.75%	0.40%	3.4%	1.85%	2.05%	1.85%
thrust	1.8%	1.75%	3.0%	3.15%	4.7%	4.6%
torque	1.05%	0.95%	3.15%	0.9%	1.8%	1.55%
SHP	0.85%	0.7%	3.1%	1.2%	0.9%	0.9%

The prediction-uncertainties for case F, which only considers the contribution of full-scale uncertainties (with all other sources of uncertainties ignored), are roughly comparable (although somewhat smaller on the whole) to the uncertainties for case M3, which only considers the contribution of model-scale uncertainties (with all other sources of uncertainties ignored).

Case MF : contribution of model-scale and full-scale uncertainties

The contributions of both the model-scale uncertainties and the full-scale uncertainties considered in cases M3 and F, respectively, are now combined. The prediction-uncertainties Uspeed, Urpm, Uthrust, Utorque, USHP and UEHP for the full-scale speed, rpm, thrust, torque, SHP and EHP for this case, called MF hereafter, are listed in the next table for five cases corresponding to predictions for a specified value of the full-scale speed, rpm, thrust, torque or SHP .

Full-scale prediction-uncertainties for case MF

at given	Uspeed	Urpm	Uthrust	Utorque	USHP	UEHP
speed	0.6%	0.85%	4.8%	3.9%	4.1%	3.25%
rpm	0.85%	0.4%	4.8%	4.0%	4.1%	3.3%
thrust	2.45%	2.5%	3.0%	4.5%	6.35%	5.85%
torque	2.0%	2.1%	4.5%	0.9%	2.55%	2.1%
SHP	1.4%	1.4%	4.15%	1.7%	0.9%	2.45%

The uncertainties for case MF are larger than the uncertainties for either case M3 or case F, as one expects.

Case MFC : sensitivity to variations in the correlation allowance

The prediction-uncertainties for case MF are based on the assumption that the correlation allowance is known without uncertainty. However, variations in the value of the correlation allowance occur, due to variations in the full-scale submarine that are not accounted for in the model tests (e.g. variations in the hull roughness) as well as uncertainties attached to both model-scale and full-scale variables. As is noted in the introduction, bias errors systematically introduced at model scale and full scale are largely, although not fully, included in the correlation allowance.

The correlation allowance is taken equal to 0.0005 for the typical case examined in the present uncertainty analysis. Experience with the SSN 688 class submarines indicates variations of the correlation allowance within a fairly broad range. Inasmuch as the contributions of model-scale and full-scale uncertainties are already included in the full-scale prediction-uncertainties obtained in case MF, a 20% variation of the correlation allowance is considered here, i.e. variations of the correlation allowance CA within the range

$$CA = 0.0005 +/- 0.0001$$

are considered in case MFC . Thus, the prediction-uncertainties obtained when the effect of a 20% variation in the value of the correlation allowance is added to the model-scale and full-scale uncertainties considered in case MF is examined in case MFC .

The prediction-uncertainties Uspeed, Urpm, Uthrust, Utorque, USHP and UEHP for the full-scale speed, rpm, thrust, torque, SHP and EHP for this case, called case MFC, are listed in the next table for five cases corresponding to predictions for a specified value of the full-scale speed, rpm, thrust, torque or SHP .

Full-scale prediction-uncertainties for case MFC

at given	Uspeed	Urpm	Uthrust	Utorque	USHP	UEHP
speed	0.6%	0.85%	6.0%	5.35%	5.45%	4.9%
rpm	0.85%	0.4%	6.0%	5.4%	5.5%	4.9%
thrust	3.1%	3.1%	3.0%	4.5%	6.6%	6.15%
torque	2.75%	2.8%	4.5%	0.9%	3.2%	2.8%
SHP	1.85%	1.85%	4.35%	2.1%	0.9%	2.45%

The uncertainties for case MFC are larger than the uncertainties for case MF, as one expects.

CONCLUSION

In summary, a tool for estimating the uncertainties attached to full-scale predictions of submarine resistance and propulsion based on standard submarine tow-tank model tests has been developed, using a global uncertainty analysis, and applied to a typical case. The analysis takes into account the uncertainties associated with the prediction procedure and the uncertainties of measurements performed both at model scale and at full scale. Thus, the uncertainty analysis developed and applied here takes into account all the component uncertainties which influence the overall uncertainty of full-scale predictions.

Estimates of the prediction-uncertainties Uspeed, Urpm, Uthrust, Utorque, USHP and UEHP attached to the full-scale speed, rpm, thrust, torque, SHP and EHP have been obtained for five cases, which correspond to predictions for a specified value of the full-scale speed, rpm, thrust, torque or SHP. The prediction-uncertainties for a specified value of the full-scale shaft horsepower are on the whole somewhat smaller than the prediction-uncertainties corresponding to a specified value of the full-scale speed, rpm, thrust, or torque. Estimates of the prediction-uncertainties Uspeed, Urpm, Uthrust, Utorque, USHP and UEHP are given for six cases, called M1, M2, M3, F, MF and MFC.

The prediction-uncertainties for case M1 represent the contribution of precision errors of model-scale measurements when all other sources of errors (including bias errors of model-scale measurements, uncertainties of the density and the viscosity of tank water, and model-scale geometrical inaccuracies) are ignored. Thus, bias errors attached to the measured primary model-scale variables are not taken into account in case M1, which corresponds to successive model tests within a series of consecutive tests.

The contribution of uncertainties of the density and the viscosity of tank water, the model length and area, and the propeller diameter, are considered in case

M2. The uncertainties of full-scale predictions for case M2 are not appreciably larger than those obtained for case M1. Thus, the uncertainties of the density and the viscosity of tank water, of the length and the area of the model, and of the diameter of the propeller are sufficiently small that they have insignificant effect upon the prediction-uncertainties.

The sensitivity of prediction-uncertainties to model-scale bias errors is considered in case M3. Model-scale bias errors are taken equal to the model-scale precision (random) errors considered in cases M1 and M2. Thus, the prediction-uncertainties for case M3 are equal to $2^{1/2}$ times the prediction-uncertainties for case M2 as one expects. The prediction-uncertainties for case M3 may be regarded as the uncertainties of the full-scale predictions obtained using standard submarine model testing in the tow-tank for a specified full-scale submarine and propeller geometry and specified full-scale conditions.

Comparison of full-scale predictions to measurements in full-scale trials introduces additional uncertainties. These additional full-scale uncertainties stem from the uncertainties in the values of the density and the viscosity of sea water, the geometry of the full-scale ship and propeller, and the values of the full-scale speed, propeller rpm, thrust, torque, and shaft horsepower. The contribution of these full-scale uncertainties to the prediction-uncertainties is considered in case F , which only considers the contribution of full-scale uncertainties (with all other sources of uncertainties ignored). The prediction-uncertainties for case F are roughly comparable (although somewhat smaller on the whole) to the uncertainties for case M3, which only considers the contribution of model-scale uncertainties (with all other sources of uncertainties ignored).

The contributions of both the model-scale uncertainties and the full-scale uncertainties considered in cases M3 and F , respectively, are combined in case MF. Thus, the uncertainties for case MF are larger than the uncertainties for either case

M3 or case F . The prediction-uncertainties for case MF are based on the assumption that the correlation allowance is known without uncertainty.

However, variations in the value of the correlation allowance occur, due to variations in the full-scale submarine (such as variations in the hull roughness) that are not accounted for in the model tests, as well as uncertainties attached to both model-scale and full-scale variables. As is noted in the introduction, bias errors systematically introduced by the prediction procedure and measurements at model scale and full scale are largely, although not fully, included in the correlation allowance. Inasmuch as the contributions of model-scale and full-scale uncertainties are already included in the full-scale prediction-uncertainties evaluated in case MF, the effect of a 20% variation in the value of the correlation allowance added to the model-scale and full-scale uncertainties determined in case MF is examined in case MFC .

The cases M1, M2, M3, F, MF and MFC are summarized below

Cases M1, M2, M3, F, MF and MFC

M1	only considers precision uncertainties of model-scale measurements
M2	adds uncertainties of tank-water properties and model-scale geometry
M3	considers all model-scale precision and bias uncertainties
F	only considers full-scale uncertainties
MF	considers all model-scale and full-scale uncertainties
MFC	adds sensitivity to variations in correlation allowance

The prediction-uncertainties Uspeed, Urpm, Uthrust, Utorque, USHP and UEHP for a specified value of the full-scale SHP are listed in the following table for

the six cases M1, M2, M3, F, MF and MFC. The uncertainty UPC of the propulsive efficiency is also given in the table

Full-scale prediction-uncertainties for a specified SHP

case	Uspeed	Urpm	Uthrust	Utorque	USHP	UEHP	UPC
M1	0.7%	0.8%	2.0%	0.8%	n/a	1.6%	1.6%
M2	0.8%	0.9%	2.0%	0.9%	n/a	1.6%	1.6%
M3	1.1%	1.2%	2.8%	1.2%	n/a	2.3%	2.3%
F	0.8%	0.7%	3.1%	1.2%	0.9%	0.9%	n/a
MF	1.4%	1.4%	4.2%	1.7%	0.9%	2.4%	2.3%
MFC	1.9%	1.9%	4.3%	2.1%	0.9%	2.4%	2.3%

In summary, it may be concluded that the full-scale prediction-uncertainties for a specified SHP are approximately equal to

Summary of full-scale prediction-uncertainties for a specified SHP

Uspeed	Urpm	Uthrust	Utorque	USHP	UEHP	UPC
2%	2%	4%	2%	1%	2%	2%

APPENDIX A : PREDICTION PROCEDURE

Primary model-scale variables

Primary model-scale variables are determined from measurements. Five major primary variables are measured : the carriage speed V , the drag R , and the propeller rps n , thrust T and torque Q .

Transformed model-scale variables

Transformed model-scale variables are obtained from the measured primary variables by means of analytical relations. The major transformed model-scale variables are the total-drag coefficient C_T , the friction-drag coefficient C_F , the residuary-drag coefficient C_R , the advance ratio J_V , the thrust-deduction factor $1 - t$ and the propulsive efficiency η_D . The relations defining these transformed variables are given below.

The total-drag coefficient C_T of the model in a resistance (EHP) test is given by the relation

$$C_T = \frac{R_T}{\rho S V^2 / 2} \quad (1)$$

where R_T is the drag of the model (without propeller), ρ is the density of the tank water, S is the wetted-surface area of the model, and V is the carriage speed. The friction-drag coefficient C_F of the model is evaluated using the ITTC formula

$$C_F = 0.075 / (C \ln R_n - 2)^2 \quad (2a)$$

where $C \approx 0.4342944819$. The Reynolds number R_n is defined as

$$R_n = VL / \nu \quad (2b)$$

where L is the length of the model and ν is the kinematic viscosity of the tank water. The residuary-drag coefficient C_R is defined by the relation

$$C_R = C_T - C_F \quad (3)$$

where C_T and C_F are given by (1) and (2), respectively. The residuary-drag coefficient C_R is evaluated at low speed, so that free-surface effects may be neglected.

Propulsion tests yield the ideal resistance R_i

$$R_i = R_T - \Delta R \quad (4)$$

where R_T is the drag of the model without propeller and ΔR is the change in the tow force due to the propeller. The total-drag coefficient C_T of the model in a propulsion test is given by

$$C_T = \frac{R_i}{\rho S V^2 / 2} \quad (5)$$

The advance ratio J_V is defined as

$$J_V = V / (nD) \quad (6)$$

where n and D are the propeller rps and diameter. The thrust-deduction factor $1-t$ is given by

$$1-t = R_i / T \quad (7)$$

where T is the propeller thrust. The propulsive efficiency η_D is

$$\eta_D = \frac{VR_i}{2\pi n Q} \quad (8)$$

where Q is the propeller torque. The three curves representing the nondimensional variables J_V , $1-t$ and η_D as functions of C_T are used to determine full-scale predictions.

Full-scale predictions

The superscript S identifies full-scale variables. No superscript is used for model-scale variables. At a given ship speed V^S , the total-drag coefficient C_T^S , the propeller rps n^S , thrust T^S and torque Q^S , and the shaft horsepower SHP^S are determined using the relations given below.

The friction-drag coefficient C_F^S is determined using the ITTC formula

$$C_F^S = 0.075 / (C \ln R_n^S - 2)^2 \quad (9a)$$

where $C \approx 0.4342944819$. The Reynolds number R_n^S is defined as

$$R_n^S = V^S L^S / \nu^{sea} \quad (9b)$$

where L^S is the ship length and ν^{sea} is the kinematic viscosity of sea water. The total-drag coefficient C_T^S of the ship is evaluated using the relation

$$C_T^S = C_F^S + C_R + C_A \quad (10)$$

Here, C_F^S is the friction-drag coefficient, C_R is the residuary-drag coefficient determined from model tests, and the correlation allowance C_A accounts for differences between the actual drag coefficient C_T^S and the predicted drag coefficient $C_F^S + C_R$.

The propeller rps is obtained from the relation

$$n^S = \frac{V^S}{J_V^S D^S} \quad (11)$$

where D^S is the propeller diameter. Furthermore, the advance ratio J_V^S is determined from the function $J_V(C_T)$ obtained from model tests, with C_T taken equal to the full-scale value C_T^S predicted by (10).

The total drag of the ship R_T^S and the power required to overcome R_T^S are given by

$$R_T^S = C_T^S \rho^{sea} S^S (V^S)^2 / 2$$

$$EHP^S = R_T^S V^S = C_T^S \rho^{sea} S^S (V^S)^3 / 2 \quad (12)$$

where ρ^{sea} is the density of sea water and S^S is the wetted surface of the ship.

The thrust T^S exerted by the propeller is evaluated using the relation

$$T^S = \frac{R_T^S}{1-t^S} = \frac{C_T^S}{1-t^S} \rho^{sea} S^S (V^S)^2 / 2 \quad (13)$$

where the thrust-deduction factor $1-t^S$ is determined from the function $(1-t)(C_T)$ obtained from model tests, with C_T taken equal to the full-scale value C_T^S given by (10).

The power provided to the propeller is

$$SHP^S = \frac{EHP^S}{\eta_D^S} = \frac{C_T^S}{\eta_D^S} \rho^{sea} S^S (V^S)^3 / 2 \quad (14)$$

where the propulsive efficiency η_D^S is determined from the function $\eta_D(C_T)$ obtained from model tests, with C_T taken equal to the full-scale value C_T^S given by (10).

Finally, the propeller torque Q^S is defined by

$$Q^S = \frac{SHP^S}{2\pi n^S} = \frac{C_T^S J_V^S D^S}{4\pi \eta_D^S} \rho^{sea} S^S (V^S)^2 \quad (15)$$

where (14) and (11) were used.

The foregoing relations yield values of the shaft horsepower SHP^S corresponding to a range of values of the ship speed V^S . A plot of the speed V^S as a function of the horsepower SHP^S is then used to determine the ship speed V^S corresponding to a prescribed value of the power SHP^S .

APPENDIX B : GLOBAL UNCERTAINTY ANALYSIS

Uncertainties of measured model-scale variables

The previous relations, which define model-scale and full-scale variables in terms of five measured primary model-scale variables (speed V , drag R , and propeller rps n , thrust T and torque Q), can be used to determine the uncertainties of the transformed model-scale variables and of the predicted full-scale variables in terms of the uncertainties of the measured primary variables. These analytical expressions for the uncertainties of the transformed model-scale variables and of the full-scale predictions are given below.

Uncertainties of transformed model-scale variables

Expression (1) yields

$$\frac{dC_T}{C_T} = \frac{dR_T}{R_T} - \frac{d\rho}{\rho} - \frac{dS}{S} - 2 \frac{dV}{V} \quad (16)$$

Using (2) we obtain

$$\frac{dC_F}{C_F} = \frac{-2C}{C \ln R_n - 2} \frac{dR_n}{R_n} = \frac{-2C}{\sqrt{0.075}} \sqrt{C_F} \left(\frac{dV}{V} + \frac{dL}{L} - \frac{d\nu}{\nu} \right) = -\sqrt{\hat{C} C_F} \left(\frac{dV}{V} + \frac{dL}{L} - \frac{d\nu}{\nu} \right)$$

where $\hat{C} = 4C^2/0.075 \simeq 10.0593$. We thus have

$$\frac{dC_F}{C_F} = -\sqrt{10 C_F} \left(\frac{dV}{V} + \frac{dL}{L} - \frac{d\nu}{\nu} \right) \quad (17)$$

Expression (3) yields

$$dC_R = C_T \frac{dC_T}{C_T} - C_F \frac{dC_F}{C_F}$$

By using (16) and (17) we obtain

$$dC_R = C_T \left(\frac{dR_T}{R_T} - \frac{d\rho}{\rho} - \frac{dS}{S} \right) + C_F \sqrt{10 C_F} \left(\frac{dL}{L} - \frac{d\nu}{\nu} \right) - \left(2C_T - C_F \sqrt{10 C_F} \right) \frac{dV}{V}$$

Thus, the uncertainty of the residuary-drag coefficient is defined by

$$\begin{aligned} \left(\frac{\delta C_R}{C_T} \right)^2 &= \left(\frac{\delta R_T}{R_T} \right)^2 + \left(\frac{\delta \rho}{\rho} \right)^2 + \left(\frac{\delta S}{S} \right)^2 + 10 C_F \left(\frac{C_F}{C_T} \right)^2 \left[\left(\frac{\delta L}{L} \right)^2 + \left(\frac{\delta \nu}{\nu} \right)^2 \right] \\ &\quad + \left(2 - \sqrt{10 C_F} \frac{C_F}{C_T} \right)^2 \left(\frac{\delta V}{V} \right)^2 \end{aligned} \quad (18)$$

where δR stands for δR_T and V is the carriage speed for the resistance test used to determine C_R .

Expression (4) yields

$$dR_i = dR_T - d\Delta R$$

The absolute uncertainty of R_i therefore is given by

$$\delta R_i = \sqrt{\left(\frac{\delta R_T}{R_T} \right)^2 (R_T)^2 + \left(\frac{\delta \Delta R}{\Delta R} \right)^2 (\Delta R)^2} \quad (19)$$

Expression (5) shows that the relative uncertainty of C_T is given by

$$\left(\frac{\delta C_T}{C_T}\right)^2 = \left(\frac{\delta R_i}{R_i}\right)^2 + \left(\frac{\delta \rho}{\rho}\right)^2 + \left(\frac{\delta S}{S}\right)^2 + 4\left(\frac{\delta V}{V}\right)^2 \quad (20)$$

Expression (6) defines the relative uncertainty of the advance ratio J_V as

$$\left(\frac{\delta J_V}{J_V}\right)^2 = \left(\frac{\delta V}{V}\right)^2 + \left(\frac{\delta n}{n}\right)^2 + \left(\frac{\delta D}{D}\right)^2 \quad (21)$$

The relative uncertainty of the thrust-deduction factor $1-t$ is defined by (7) as

$$\left(\frac{\delta(1-t)}{1-t}\right)^2 = \left(\frac{\delta R_i}{R_i}\right)^2 + \left(\frac{\delta T}{T}\right)^2 \quad (22)$$

The relative uncertainty of the propulsive efficiency η_D is defined by (8) as

$$\left(\frac{\delta \eta_D}{\eta_D}\right)^2 = \left(\frac{\delta V}{V}\right)^2 + \left(\frac{\delta R_i}{R_i}\right)^2 + \left(\frac{\delta n}{n}\right)^2 + \left(\frac{\delta Q}{Q}\right)^2 \quad (23)$$

In (20) and (22)-(23), δR_i is given by (19).

Uncertainties of full-scale predictions

Expression (10) for the total-drag coefficient C_T^S yields

$$dC_T^S = dC_F^S + dC_R + dC_A$$

which may be expressed in the form

$$\frac{dC_T^S}{C_T^S} = \frac{C_F^S}{C_T^S} \frac{dC_F^S}{C_F^S} + \frac{dC_R + dC_A}{C_T^S}$$

Expressions (9), (2) and (17) show that we have

$$\frac{dC_F^S}{C_F^S} = -\sqrt{10 C_F^S} \left(\frac{dV^S}{V^S} + \frac{dL^S}{L^S} - \frac{d\nu^{sea}}{\nu^{sea}} \right) \quad (24)$$

We then have

$$\frac{dC_T^S}{C_T^S} = \Gamma \left(D_C^{L\nu} - \frac{dV^S}{V^S} \right) \quad (25)$$

where Γ and $D_C^{L\nu}$ are defined as

$$\Gamma = \sqrt{10 C_F^S} \frac{C_F^S}{C_T^S} \quad (26)$$

$$D_C^{L\nu} = \frac{dC_R + dC_A}{\sqrt{10 C_F^S C_T^S}} - \frac{dL^S}{L^S} + \frac{d\nu^{sea}}{\nu^{sea}} \quad (27)$$

Expressions (11), (13), (14) and (15) involve the nondimensional coefficients J_V , $1-t$ and η_D . These coefficients are determined from curve fits (obtained from model tests) of J_V , $1-t$

and η_D as functions of C_T . Let Λ stand for any one of the three coefficients J_V , $1-t$ and η_D . The difference in the coefficient Λ is given by

$$d\Lambda|_{C_T^S} + \frac{d\Lambda}{dC_T} dC_T^S$$

The first term represents the difference in Λ at a given value of C_T^S , and the second term defines the difference in Λ due to the uncertainty of C_T^S . Let the first term be written as $d\Lambda$ for shortness. The relative difference in Λ may then be expressed in the form

$$\frac{d\Lambda}{\Lambda} + \frac{d\Lambda}{dC_T} \frac{C_T^S}{\Lambda} \Gamma \left(D_C^{L\nu} - \frac{dV^S}{V^S} \right)$$

where (25) was used. The relative differences in the coefficients J_V , $1-t$ and η_D are then given by

$$\frac{dJ_V}{J_V} + \sigma^J \left(D_C^{L\nu} - \frac{dV^S}{V^S} \right) \quad \frac{d(1-t)}{1-t} + \sigma^t \left(D_C^{L\nu} - \frac{dV^S}{V^S} \right) \quad \frac{d\eta_D}{\eta_D} + \sigma^\eta \left(D_C^{L\nu} - \frac{dV^S}{V^S} \right) \quad (28)$$

where σ^J , σ^t and σ^η are defined as

$$\sigma^J = \sqrt{10 C_F^S} \frac{C_F^S}{J_V} \frac{dJ_V}{dC_T} \quad \sigma^t = \sqrt{10 C_F^S} \frac{C_F^S}{1-t} \frac{d(1-t)}{dC_T} \quad \sigma^\eta = \sqrt{10 C_F^S} \frac{C_F^S}{\eta_D} \frac{d\eta_D}{dC_T} \quad (29)$$

Here, expression (26) for the term Γ was used.

It is also useful to define the notation

$$D_V = \frac{dV^S}{V^S} \quad D_N = \frac{dn^S}{n^S} \quad D_T = \frac{dT^S}{T^S} \quad D_Q = \frac{dQ^S}{Q^S} \quad D_P = \frac{dSHP^S}{SHP^S} \quad (30a)$$

$$D_\rho^S = \frac{d\rho^{sea}}{\rho^{sea}} + \frac{dS^S}{S^S} \quad D_t = \frac{d(1-t)}{1-t} \quad D_\eta = \frac{d\eta_D}{\eta_D} \quad D_J^D = \frac{dJ_V}{J_V} + \frac{dD^S}{D^S} \quad (30b)$$

Expressions (11), (13), (14), (15), (25), (28) and (30) yield

$$D_N = (1 + \sigma^J) D_V - \sigma^J D_C^{L\nu} - D_J^D \quad (31a)$$

$$D_T = (2 - \Gamma + \sigma^t) D_V + (\Gamma - \sigma^t) D_C^{L\nu} + D_\rho^S - D_t \quad (31b)$$

$$D_Q = (2 - \Gamma + \sigma^\eta - \sigma^J) D_V + (\Gamma - \sigma^\eta + \sigma^J) D_C^{L\nu} + D_\rho^S - D_\eta + D_J^D \quad (31c)$$

$$D_P = (3 - \Gamma + \sigma^\eta) D_V + (\Gamma - \sigma^\eta) D_C^{L\nu} + D_\rho^S - D_\eta \quad (31d)$$

where the relative differences dJ_V^S/J_V^S , $d(1-t^S)/(1-t^S)$ and $d\eta_D^S/\eta_D^S$ have been taken equal to the corresponding model-scale values dJ_V/J_V , $d(1-t)/(1-t)$ and $d\eta_D/\eta_D$.

The four relations (31) involve model-scale variables and differences — which occur via expressions (18), (21), (22), (23) for the terms dC_R , dJ_V/J_V , $d(1-t)/(1-t)$, $d\eta_D/\eta_D$ — and full-scale variables. The full-scale variables include the relative differences $d\rho^{sea}/\rho^{sea}$, $d\nu^{sea}/\nu^{sea}$, dD^S/D^S , dL^S/L^S and dS^S/S^S (which may be determined independently and thus may be presumed known for the purpose of this uncertainty analysis), the difference dC_A (which may also be regarded as a given input for this analysis), and the five terms dV^S/V^S ,

dn^S/n^S , dT^S/T^S , dQ^S/Q^S , $dSHPS^S/SHPS^S$. Thus, four of these five terms may be determined from any one of them. Specifically, the four relations (31), which define the relative differences dn^S/n^S , dT^S/T^S , dQ^S/Q^S and $dSHPS^S/SHPS^S$ in terms of dV^S/V^S , can be expressed in the four alternative forms given below.

One alternative form of the four relations (31) is

$$(1 + \sigma^J) D_V = D_N + \sigma^J D_C^{L\nu} + D_J^D \quad (32a)$$

$$\begin{aligned} (1 + \sigma^J) D_T &= (2 - \Gamma + \sigma^t) (D_N + D_J^D) \\ &\quad + (\Gamma - \sigma^t + 2\sigma^J) D_C^{L\nu} + (1 + \sigma^J) (D_\rho^S - D_t) \end{aligned} \quad (32b)$$

$$\begin{aligned} (1 + \sigma^J) D_Q &= (2 - \Gamma + \sigma^\eta - \sigma^J) D_N + (\Gamma - \sigma^\eta + 3\sigma^J) D_C^{L\nu} \\ &\quad + (1 + \sigma^J) (D_\rho^S - D_\eta) + (3 - \Gamma + \sigma^\eta) D_J^D \end{aligned} \quad (32c)$$

$$\begin{aligned} (1 + \sigma^J) D_P &= (3 - \Gamma + \sigma^\eta) (D_N + D_J^D) + (\Gamma - \sigma^\eta + 3\sigma^J) D_C^{L\nu} \\ &\quad + (1 + \sigma^J) (D_\rho^S - D_\eta) \end{aligned} \quad (32d)$$

These relations define the relative differences dV^S/V^S , dT^S/T^S , dQ^S/Q^S and $dSHPS^S/SHPS^S$ in terms of dn^S/n^S .

The four relations (31) can similarly be expressed in the form

$$(2 - \Gamma + \sigma^t) D_V = D_T - (\Gamma - \sigma^t) D_C^{L\nu} - D_\rho^S + D_t \quad (33a)$$

$$\begin{aligned} (2 - \Gamma + \sigma^t) D_N &= (1 + \sigma^J) (D_T - D_\rho^S + D_t) - (\Gamma - \sigma^t + 2\sigma^J) D_C^{L\nu} \\ &\quad - (2 - \Gamma + \sigma^t) D_J^D \end{aligned} \quad (33b)$$

$$\begin{aligned} (2 - \Gamma + \sigma^t) D_Q &= (2 - \Gamma + \sigma^\eta - \sigma^J) (D_T + D_t) \\ &\quad + (\sigma^t - \sigma^\eta + \sigma^J) (2D_C^{L\nu} + D_\rho^S) + (2 - \Gamma + \sigma^t) (D_J^D - D_\eta) \end{aligned} \quad (33c)$$

$$\begin{aligned} (2 - \Gamma + \sigma^t) D_P &= (3 - \Gamma + \sigma^\eta) (D_T + D_t) - (\Gamma + 2\sigma^\eta - 3\sigma^t) D_C^{L\nu} \\ &\quad - (1 + \sigma^\eta - \sigma^t) D_\rho^S - (2 - \Gamma + \sigma^t) D_\eta \end{aligned} \quad (33d)$$

These relations define the relative differences dV^S/V^S , dn^S/n^S , dQ^S/Q^S and $dSHPS^S/SHPS^S$ in terms of dT^S/T^S .

A third alternative form of the four relations (31) is

$$(2 - \Gamma + \sigma^\eta - \sigma^J) D_V = D_Q - (\Gamma - \sigma^\eta + \sigma^J) D_C^{L\nu} - D_\rho^S + D_\eta - D_J^D \quad (34a)$$

$$\begin{aligned} (2 - \Gamma + \sigma^\eta - \sigma^J) D_N &= (1 + \sigma^J) (D_Q - D_\rho^S + D_\eta) - (\Gamma - \sigma^\eta + 3\sigma^J) D_C^{L\nu} \\ &\quad - (3 - \Gamma + \sigma^\eta) D_J^D \end{aligned} \quad (34b)$$

$$(2 - \Gamma + \sigma^\eta - \sigma^J) D_T = (2 - \Gamma + \sigma^t)(D_Q + D_\eta - D_J^D) - (\sigma^t - \sigma^\eta + \sigma^J)(2D_C^{L\nu} + D_\rho^S) \\ - (2 - \Gamma + \sigma^\eta - \sigma^J) D_t \quad (34c)$$

$$(2 - \Gamma + \sigma^\eta - \sigma^J) D_P = (3 - \Gamma + \sigma^\eta)(D_Q - D_J^D) - (\Gamma - \sigma^\eta + 3\sigma^J) D_C^{L\nu} \\ - (1 + \sigma^J)(D_\rho^S - D_\eta) \quad (34d)$$

These relations define the relative differences dV^S/V^S , dn^S/n^S , dT^S/T^S and $dSHP^S/SHP^S$ in terms of dQ^S/Q^S .

Finally, the four relations (31) can be expressed as

$$(3 - \Gamma + \sigma^\eta) D_V = D_P - (\Gamma - \sigma^\eta) D_C^{L\nu} - D_\rho^S + D_\eta \quad (35a)$$

$$(3 - \Gamma + \sigma^\eta) D_N = (1 + \sigma^J)(D_P - D_\rho^S + D_\eta) - (\Gamma - \sigma^\eta + 3\sigma^J) D_C^{L\nu} \\ - (3 - \Gamma + \sigma^\eta) D_J^D \quad (35b)$$

$$(3 - \Gamma + \sigma^\eta) D_T = (2 - \Gamma + \sigma^t)(D_P + D_\eta) + (\Gamma + 2\sigma^\eta - 3\sigma^t) D_C^{L\nu} \\ + (1 + \sigma^\eta - \sigma^t) D_\rho^S - (3 - \Gamma + \sigma^\eta) D_t \quad (35c)$$

$$(3 - \Gamma + \sigma^\eta) D_Q = (2 - \Gamma + \sigma^\eta - \sigma^J) D_P + (\Gamma - \sigma^\eta + 3\sigma^J) D_C^{L\nu} \\ + (1 + \sigma^J)(D_\rho^S - D_\eta) + (3 - \Gamma + \sigma^\eta) D_J^D \quad (35d)$$

These relations define the relative differences dV^S/V^S , dn^S/n^S , dT^S/T^S and dQ^S/Q^S in terms of $dSHP^S/SHP^S$.

Expressions (12) and (14) show that the relative difference

$$D_E = \frac{dEHP^S}{EHP^S} \quad (36)$$

can be obtained from the foregoing expressions for the relative difference $D_P = dSHP^S/SHP^S$. Specifically, expressions (31d), (32d), (33d) and (34d) respectively yield

$$D_E = (3 - \Gamma) D_V + \Gamma D_C^{L\nu} + D_\rho^S \quad (37a)$$

$$(1 + \sigma^J) D_E = (3 - \Gamma)(D_N + D_J^D) + (\Gamma + 3\sigma^J) D_C^{L\nu} + (1 + \sigma^J) D_\rho^S \quad (37b)$$

$$(2 - \Gamma + \sigma^t) D_E = (3 - \Gamma)(D_T + D_t) - (\Gamma - 3\sigma^t) D_C^{L\nu} - (1 - \sigma^t) D_\rho^S \quad (37c)$$

$$(2 - \Gamma - \sigma^J) D_E = (3 - \Gamma)(D_Q - D_J^D) - (\Gamma + 3\sigma^J) D_C^{L\nu} - (1 + \sigma^J) D_\rho^S \quad (37d)$$

The relations $EHP^S = \eta_D SHP^S$, (28) and (35a) yield

$$(3 - \Gamma + \sigma^\eta) D_E = (3 - \Gamma)(D_P + D_\eta) + \sigma^\eta(3D_C^{L\nu} + D_\rho^S) \quad (37e)$$

The relative uncertainties $\delta V^S/V^S$, $\delta n^S/n^S$, $\delta T^S/T^S$, $\delta Q^S/Q^S$ and $\delta SHP^S/SHP^S$ corresponding to the relative differences dV^S/V^S , dn^S/n^S , dT^S/T^S , dQ^S/Q^S and $dSHP^S/SHP^S$

defined in the foregoing alternative relations are readily determined by taking the square root of the sum of the square of every term in these relations. Thus, we define the notation

$$U_C^{L\nu} = \frac{(\delta C_R)^2 + (\delta C_A)^2}{10(C_F^S)^3} + \left(\frac{\delta L^S}{L^S}\right)^2 + \left(\frac{\delta \nu^{sea}}{\nu^{sea}}\right)^2 \quad U_\rho^S = \left(\frac{\delta \rho^{sea}}{\rho^{sea}}\right)^2 + \left(\frac{\delta S^S}{S^S}\right)^2 \quad (38a)$$

$$U_V = \left(\frac{\delta V^S}{V^S}\right)^2 \quad U_N = \left(\frac{\delta n^S}{n^S}\right)^2 \quad U_T = \left(\frac{\delta T^S}{T^S}\right)^2 \quad U_Q = \left(\frac{\delta Q^S}{Q^S}\right)^2 \quad (38b)$$

$$U_P = \left(\frac{\delta SHPS}{SHPS}\right)^2 \quad U_E = \left(\frac{\delta EHP^S}{EHP^S}\right)^2 \quad U_t = \left(\frac{\delta(1-t)}{1-t}\right)^2 \quad (38c)$$

$$U_\eta = \left(\frac{\delta \eta_D}{\eta_D}\right)^2 \quad U_J^D = \left(\frac{\delta J_V}{J_V}\right)^2 + \left(\frac{\delta D^S}{D^S}\right)^2 \quad (38d)$$

corresponding to (27) and (30). We also define the relative uncertainties attached to the full-scale measurements of V^S , n^S , T^S , Q^S , $SHPS$ and EHP^S , i.e.

$$U_V^{fsm} = \left(\frac{\delta V_{fsm}^S}{V^S}\right)^2 \quad U_N^{fsm} = \left(\frac{\delta n_{fsm}^S}{n^S}\right)^2 \quad U_T^{fsm} = \left(\frac{\delta T_{fsm}^S}{T^S}\right)^2 \quad (38e)$$

$$U_Q^{fsm} = \left(\frac{\delta Q_{fsm}^S}{Q^S}\right)^2 \quad U_P^{fsm} = \left(\frac{\delta SHP_{fsm}^S}{SHP^S}\right)^2 \quad U_E^{fsm} = \left(\frac{\delta EHP_{fsm}^S}{EHP^S}\right)^2 \quad (38f)$$

where the subscript or superscript *fsm* means *full-scale measurement*. In practice, the uncertainty U_E^{fsm} attached to the effective horsepower EHP^S of the ship is not defined because measurements of EHP_{fsm}^S are not available. Thus, the term EHP_{fsm}^S in the expressions given below may be ignored in practice.

Expressions (31) and (37a) yield

$$U_N = (1 + \sigma^J)^2 U_V^{fsm} + (\sigma^J)^2 U_C^{L\nu} + U_J^D + U_N^{fsm} \quad (39a)$$

$$U_T = (2 - \Gamma + \sigma^t)^2 U_V^{fsm} + (\Gamma - \sigma^t)^2 U_C^{L\nu} + U_\rho^S + U_t + U_T^{fsm} \quad (39b)$$

$$U_Q = (2 - \Gamma + \sigma^\eta - \sigma^J)^2 U_V^{fsm} + (\Gamma - \sigma^\eta + \sigma^J)^2 U_C^{L\nu} + U_\rho^S + U_\eta + U_J^D + U_Q^{fsm} \quad (39c)$$

$$U_P = (3 - \Gamma + \sigma^\eta)^2 U_V^{fsm} + (\Gamma - \sigma^\eta)^2 U_C^{L\nu} + U_\rho^S + U_\eta + U_P^{fsm} \quad (39d)$$

$$U_E = (3 - \Gamma)^2 U_V^{fsm} + \Gamma^2 U_C^{L\nu} + U_\rho^S + U_E^{fsm} \quad (39e)$$

Similarly, (32) and (37b) yield

$$(1 + \sigma^J)^2 U_V = U_N^{fsm} + (\sigma^J)^2 U_C^{L\nu} + U_J^D + (1 + \sigma^J)^2 U_V^{fsm} \quad (40a)$$

$$(1 + \sigma^J)^2 U_T = (2 - \Gamma + \sigma^t)^2 (U_N^{fsm} + U_J^D) + (\Gamma - \sigma^t + 2\sigma^J)^2 U_C^{L\nu} \\ + (1 + \sigma^J)^2 (U_\rho^S + U_t + U_T^{fsm}) \quad (40b)$$

$$(1+\sigma^J)^2 U_Q = (2-\Gamma+\sigma^\eta-\sigma^J)^2 U_N^{fsm} + (\Gamma-\sigma^\eta+3\sigma^J)^2 U_C^{L\nu} \\ + (3-\Gamma+\sigma^\eta)^2 U_J^D + (1+\sigma^J)^2 (U_\rho^S + U_\eta + U_Q^{fsm}) \quad (40c)$$

$$(1+\sigma^J)^2 U_P = (3-\Gamma+\sigma^\eta)^2 (U_N^{fsm} + U_J^D) + (\Gamma-\sigma^\eta+3\sigma^J)^2 U_C^{L\nu} \\ + (1+\sigma^J)^2 (U_\rho^S + U_\eta + U_P^{fsm}) \quad (40d)$$

$$(1+\sigma^J)^2 U_E = (3-\Gamma)^2 (U_N^{fsm} + U_J^D) + (\Gamma+3\sigma^J)^2 U_C^{L\nu} \\ + (1+\sigma^J)^2 (U_\rho^S + U_E^{fsm}) \quad (40e)$$

Expressions (33) and (37c) yield

$$(2-\Gamma+\sigma^t)^2 U_V = U_T^{fsm} + (\Gamma-\sigma^t)^2 U_C^{L\nu} + U_\rho^S + U_t + (2-\Gamma+\sigma^t)^2 U_V^{fsm} \quad (41a)$$

$$(2-\Gamma+\sigma^t)^2 U_N = (1+\sigma^J)^2 (U_T^{fsm} + U_\rho^S + U_t) + (\Gamma-\sigma^t+2\sigma^J)^2 U_C^{L\nu} \\ + (2-\Gamma+\sigma^t)^2 (U_J^D + U_N^{fsm}) \quad (41b)$$

$$(2-\Gamma+\sigma^t)^2 U_Q = (2-\Gamma+\sigma^\eta-\sigma^J)^2 (U_T^{fsm} + U_t) + (\sigma^t-\sigma^\eta+\sigma^J)^2 (4U_C^{L\nu} + U_\rho^S) \\ + (2-\Gamma+\sigma^t)^2 (U_J^D + U_\eta + U_Q^{fsm}) \quad (41c)$$

$$(2-\Gamma+\sigma^t)^2 U_P = (3-\Gamma+\sigma^\eta)^2 (U_T^{fsm} + U_t) + (\Gamma+2\sigma^\eta-3\sigma^t)^2 U_C^{L\nu} \\ + (1+\sigma^\eta-\sigma^t)^2 U_\rho^S + (2-\Gamma+\sigma^t)^2 (U_\eta + U_P^{fsm}) \quad (41d)$$

$$(2-\Gamma+\sigma^t)^2 U_E = (3-\Gamma)^2 (U_T^{fsm} + U_t) + (\Gamma-3\sigma^t)^2 U_C^{L\nu} \\ + (1-\sigma^t)^2 U_\rho^S + (2-\Gamma+\sigma^t)^2 U_E^{fsm} \quad (41e)$$

Expressions (34) and (37d) yield

$$(2-\Gamma+\sigma^\eta-\sigma^J)^2 U_V = U_Q^{fsm} + (\Gamma-\sigma^\eta+\sigma^J)^2 U_C^{L\nu} + U_\rho^S + U_\eta + U_J^D \\ + (2-\Gamma+\sigma^\eta-\sigma^J)^2 U_V^{fsm} \quad (42a)$$

$$(2-\Gamma+\sigma^\eta-\sigma^J)^2 U_N = (1+\sigma^J)^2 (U_Q^{fsm} + U_\rho^S + U_\eta) + (\Gamma-\sigma^\eta+3\sigma^J)^2 U_C^{L\nu} \\ + (3-\Gamma+\sigma^\eta)^2 U_J^D + (2-\Gamma+\sigma^\eta-\sigma^J)^2 U_N^{fsm} \quad (42b)$$

$$(2-\Gamma+\sigma^\eta-\sigma^J)^2 U_T = (2-\Gamma+\sigma^t)^2 (U_Q^{fsm} + U_\eta + U_J^D) + (\sigma^t-\sigma^\eta+\sigma^J)^2 (4U_C^{L\nu} + U_\rho^S) \\ + (2-\Gamma+\sigma^\eta-\sigma^J)^2 (U_t + U_T^{fsm}) \quad (42c)$$

$$(2-\Gamma+\sigma^\eta-\sigma^J)^2 U_P = (3-\Gamma+\sigma^\eta)^2 (U_Q^{fsm} + U_J^D) + (\Gamma-\sigma^\eta+3\sigma^J)^2 U_C^{L\nu} \\ + (1+\sigma^J)^2 (U_\rho^S + U_\eta) + (2-\Gamma+\sigma^\eta-\sigma^J)^2 U_P^{fsm} \quad (42d)$$

$$(2 - \Gamma - \sigma^J)^2 U_E = (3 - \Gamma)^2 (U_Q^{fsm} + U_J^D) + (\Gamma + 3\sigma^J)^2 U_C^{L\nu} \\ + (1 + \sigma^J)^2 U_\rho^S + (2 - \Gamma - \sigma^J)^2 U_E^{fsm} \quad (42e)$$

Finally, (35) and (37e) yield

$$(3 - \Gamma + \sigma^\eta)^2 U_V = U_P^{fsm} + (\Gamma - \sigma^\eta)^2 U_C^{L\nu} + U_\rho^S + U_\eta + (3 - \Gamma + \sigma^\eta)^2 U_V^{fsm} \quad (43a)$$

$$(3 - \Gamma + \sigma^\eta)^2 U_N = (1 + \sigma^J)^2 (U_P^{fsm} + U_\rho^S + U_\eta) + (\Gamma - \sigma^\eta + 3\sigma^J)^2 U_C^{L\nu} \\ + (3 - \Gamma + \sigma^\eta)^2 (U_J^D + U_N^{fsm}) \quad (43b)$$

$$(3 - \Gamma + \sigma^\eta)^2 U_T = (2 - \Gamma + \sigma^t)^2 (U_P^{fsm} + U_\eta) + (\Gamma + 2\sigma^\eta - 3\sigma^t)^2 U_C^{L\nu} \\ + (1 + \sigma^\eta - \sigma^t)^2 U_\rho^S + (3 - \Gamma + \sigma^\eta)^2 (U_t + U_T^{fsm}) \quad (43c)$$

$$(3 - \Gamma + \sigma^\eta)^2 U_Q = (2 - \Gamma + \sigma^\eta - \sigma^J)^2 U_P^{fsm} + (\Gamma - \sigma^\eta + 3\sigma^J)^2 U_C^{L\nu} \\ + (1 + \sigma^J)^2 (U_\rho^S + U_\eta) + (3 - \Gamma + \sigma^\eta)^2 (U_J^D + U_Q^{fsm}) \quad (43d)$$

$$(3 - \Gamma + \sigma^\eta)^2 U_E = (3 - \Gamma)^2 (U_P^{fsm} + U_\eta) + (\sigma^\eta)^2 (9U_C^{L\nu} + U_\rho^S) \\ + (3 - \Gamma + \sigma^\eta)^2 U_E^{fsm} \quad (43e)$$

The five sets of alternative expressions (39) through (43), and expressions (38), (29) and (26), define the uncertainties attached to the full-scale predictions of the ship speed V^S , the propeller rpm N^S , thrust T^S and torque Q^S , the shaft horsepower SHP^S and the effective horsepower $EHPS$ for five cases, in which V^S , N^S , T^S , Q^S or SHP^S are held constant (within the accuracy of full-scale measurements).

APPENDIX C: FORTRAN-CODE & INPUT-OUTPUT FILES

The source file UA3.f of the program UA3 , which represents the (third version) Fortran implementation of the uncertainty analysis expounded in Appendix B , is given in Appendix C. The symbols defined in the analysis and used in the Fortran-code UA3 are fairly consistent.

An example of the input file UA3.in required by UA3.f , and of the corresponding output file UA3.out generated by UA3.f , is also given in this Appendix. The attached example input file UA3.in and output file UA3.out corresponds to the previously-defined case MFC , in which the uncertainties attached to model-scale and full-scale variables and to the value of the correlation coefficient are included.

FORTRAN CODE

```
c
c General uncertainty analysis of full-scale resistance
c and propulsion predictions using tow-tank model tests
c Francis Noblesse (May 97 ; modified June 97)
c
c program UA3
c
c character TTxp*50 , date*50 , model*50 , prop*50 ,
& EHPxp*50 , SHPxp*50 , comment*80
c
c real ro , nu , Uro , Unu , L , S , D , UL , US , UD , VCRknot ,
& RTCR , URTCR , Vknot , RT , DelR , nrpm , T , Qinlb ,
& UV , URT , UDelR , Un , UT , UQ , JVCT , tdCT , etaCT ,
& nusea , Uros , Unus , LS , VS knot , ULS , USS , UDS ,
& UV fsm , UN fsm , UT fsm , UQ fsm , UP fsm , CA , dCA ,
& VCR , V , VS , n , Q , CTCR , CFCR , CR , Ri , CT , CF ,
& JV , td , eta , Uro2 , Unu2 , UL2 , US2 , UD2 , URTCR2 ,
& UV2 , URi , URi2 , Un2 , UT2 , UQ2 , UCA ,
& UCTCR2 , UCTCR , UCFCR2 , UCFCR , dCR2 , UCR ,
& UCT2 , UCT , UCF2 , UCF ,
& UJV2 , Utd2 , Ueta2 , UJV , Utd , Ueta ,
& CFS , CTS , UroS2 , UJD2 , cofCFS , UCLnu2 ,
& Gamma , sigmaJ , sigmat , sigmeta ,
& UV fsm2 , UN fsm2 , UT fsm2 , UQ fsm2 , UP fsm2 ,
& UN2V , UT2V , UQ2V , UP2V , UE2V ,
& UVV , UNV , UTV , UQV , UPV , UEV , UAV ,
& UV2N , UT2N , UQ2N , UP2N , UE2N ,
& UNN , UVN , UTN , UQN , UPN , UEN , UAN ,
& UV2T , UN2T , UQ2T , UP2T , UE2T ,
& UTT , UVT , UNT , UQT , UPT , UET , UAT ,
& UV2Q , UN2Q , UT2Q , UP2Q , UE2Q ,
& UQQ , UVQ , UNQ , UTQ , UPQ , UEQ , UAQ ,
& UV2P , UN2P , UT2P , UQ2P , UE2P ,
& UPP , UVP , UNP , UTP , UQP , UEP , UAP
c
c READ INPUT VARIABLES
c
c open(11,file='UA3.in',status='old')
c
read(11,*) TTxp
read(11,*) date
read(11,*) model
```

```
read(11,*) prop
read(11,*) EHPxp
read(11,*) SHPxp
read(11,*) comment
read(11,*) 
read(11,*) 
read(11,*) 
read(11,*) 
read(11,*) 
read(11,*) ro , nu
read(11,*) 
read(11,*) 
read(11,*) 
read(11,*) 
read(11,*) Uro, Unu
read(11,*) 
read(11,*) 
read(11,*) 
read(11,*) 
read(11,*) L , S , D
read(11,*) 
read(11,*) 
read(11,*) 
read(11,*) 
read(11,*) UL , US , UD
read(11,*) 
read(11,*) 
read(11,*) 
read(11,*) 
read(11,*) 
read(11,*) VCRknot , RTCR
read(11,*) 
read(11,*) 
read(11,*) 
read(11,*) URTCR
read(11,*) 
read(11,*) 
read(11,*) 
read(11,*) 
read(11,*) 
read(11,*) 
read(11,*) Vknot , RT , DelR
read(11,*) 
read(11,*) 
read(11,*) 
read(11,*) 
read(11,*) nrpm , T , Qinlb
read(11,*) 
read(11,*) 
read(11,*) 
read(11,*) 
read(11,*) UV , URT , UDelR , Un , UT , UQ
read(11,*) 
read(11,*) 
read(11,*) 
read(11,*) 
read(11,*) JVCT , tdCT , etaCT
```

```

read(11,*)
read(11,*)
read(11,*)
read(11,*)
read(11,*)
read(11,*) nusea
read(11,*)
read(11,*)
read(11,*)
read(11,*) Uros , Unus
read(11,*)
read(11,*)
read(11,*)
read(11,*) LS , VS knot
read(11,*)
read(11,*)
read(11,*)
read(11,*)
read(11,*) ULS , USS , UDS
read(11,*)
read(11,*)
read(11,*)
read(11,*)
read(11,*) UV fsm , UN fsm , UT fsm , UQ fsm , UP fsm
read(11,*)
read(11,*)
read(11,*)
read(11,*)
read(11,*) CA , dCA
c
c   close(11,status='keep')
c
c   About notation :
c   U stands for relative Uncertainty
c   fsm stands for Full-Scale Measurement uncertainty
c
c   PRELIMINARY TRANSFORMATIONS
c
c   Rescale nu and nusea
c
c   nu = nu / 100000.
c   nusea = nusea / 100000.
c
c   Transform speeds from knots to ft/sec
c
c   VCR = 1.6878 * VCRknot
c   V = 1.6878 * Vknot
c   VS = 1.6878 * VS knot
c

```

```

c      Transform rpm into rps
c
c      n = nrpm / 60.
c
c      Transform torque from in-lb to ft-lb
c
c      Q = Qinlb / 12.
c
c      Transform input percent uncertainties
c
c      Uro = 0.01 * Uro
c      Unu = 0.01 * Unu
c
c      UL = 0.01 * UL
c      US = 0.01 * US
c      UD = 0.01 * UD
c
c      URTCR = 0.01 * URTCR
c      UV = 0.01 * UV
c      URT = 0.01 * URT
c      UDelR = 0.01 * UDelR
c
c      Un = 0.01 * Un
c      UT = 0.01 * UT
c      UQ = 0.01 * UQ
c
c      Uros = 0.01 * Uros
c      Unus = 0.01 * Unus
c
c      ULS = 0.01 * ULS
c      USS = 0.01 * USS
c      UDS = 0.01 * UDS
c
c      UVfsm = 0.01 * UVfsm
c      UNfsm = 0.01 * UNfsm
c      UTfsm = 0.01 * UTfsm
c      UQfsm = 0.01 * UQfsm
c      UPfsm = 0.01 * UPfsm
c
c      MODEL-SCALE VARIABLES : RESISTANCE TESTS
c
c      Compute CTCR , CFCR & CR
c
c      CTCR = 2. * RTCR / ( ro * S * VCR * VCR )
c      CFCR = 0.075 / ( LOG10( VCR * L / nu ) - 2. )**2
c      CR = CTCR - CFCR

```

```

c
c MODEL-SCALE VARIABLES : PROPULSION TESTS
c
c Compute Ri , CT & CF
c
Ri = RT - DelR
CT = 2. * Ri / ( ro * S * V * V )
CF = 0.075 / ( LOG10( V * L / nu ) - 2. )**2
c
c Compute JV , td=1-t & eta=etaD
c
JV = V / ( n * D )
td = Ri / T
eta = V * Ri / ( 6.2831853 * n * Q )
c
c PRELIMINARY CALCULATIONS FOR MODEL-SCALE UNCERTAINTIES
c
Uro2 = Uro * Uro
Unu2 = Unu * Unu
c
UL2 = UL * UL
US2 = US * US
UD2 = UD * UD
c
URTCR2 = URTCR * URTCR
UV2 = UV * UV
c
URI = ( URT * RT )**2 + ( UDelR * DelR )**2
URI = SQRT( URI ) / Ri
URI2 = URI * URI
c
Un2 = Un * Un
UT2 = UT * UT
UQ2 = UQ * UQ
c
c MODEL-SCALE UNCERTAINTIES : RESISTANCE TESTS
c
c Compute dCTCR / CTCR
c
UCTCR2 = URTCR2 + Uro2 + US2 + 4. * UV2
UCTCR = 100. * SQRT( UCTCR2 )
c
c Compute dCFCR / CFCR
c
UCFCR2 = 10. * CFCR * ( UV2 + UL2 + Unu2 )
UCFCR = 100. * SQRT( UCFCR2 )

```

```

c
c Compute dCR^2 & dCR / CR
c
dCR2 = UV2 * ( 2. * CTCR - CFCR * SQRT( 10. * CFCR ) )**2
dCR2 = dCR2 + ( URTCR2 + Uro2 + US2 ) * CTCR**2
dCR2 = dCR2 + ( UL2 + Unu2 ) * 10. * CFCR**3
UCR = 100. * SQRT( dCR2 ) / CR

c
c MODEL-SCALE UNCERTAINTIES : PROPULSION TESTS
c
c Compute dCT / CT
c
UCT2 = URi2 + Uro2 + US2 + 4. * UV2
UCT = 100. * SQRT( UCT2 )

c
c Compute dCF / CF
c
UCF2 = 10. * CF * ( UV2 + UL2 + Unu2 )
UCF = 100. * SQRT( UCF2 )

c
c Compute dJV / JV , dtd / td & data / eta
c
UJV2 = UV2 + Un2 + UD2
Utd2 = URi2 + UT2
Ueta2 = UV2 + URi2 + Un2 + UQ2

c
UJV = 100. * SQRT( UJV2 )
Utd = 100. * SQRT( Utd2 )
Ueta = 100. * SQRT( Ueta2 )

c
c PRELIMINARY CALCULATIONS FOR FULL-SCALE UNCERTAINTIES
c
c Compute CFS & CTS
c
CFS = 0.075 / ( LOG10( VS * LS / nusea ) - 2. )**2
CTS = CFS + CR + CA

c
c Compute (drhosea/rhosea)^2+(dSS/SS)^2 & (dJV/JV)^2+(dDS/DS)^2
c
UroS2 = Uros**2 + USS**2
UJD2 = UJV2 + UDS**2

c
c Compute UCLnu2 & Gamma
c
cofCFS = 10. * CFS**3
UCLnu2 = ( dCR2 + dCA**2 ) / cofCFS + ULS**2 + Unus**2

```

```

cofCFS = SQRT( cofCFS )
Gamma = cofCFS / CTS
c
c Compute sigmaJ , sigmat & sigmeta
c
sigmaJ = cofCFS * JVCT / JV
sigmat = cofCFS * tdCT / td
sigmeta = cofCFS * etaCT / eta
c
c Compute squares of full-scale measurement uncertainties
c
UVfsm2 = UVfsm * UVfsm
UNfsm2 = UNfsm * UNfsm
UTfsm2 = UTfsm * UTfsm
UQfsm2 = UQfsm * UQfsm
UPfsm2 = UPfsm * UPfsm
c
c FULL-SCALE UNCERTAINTIES @ a GIVEN SPEED
c
UN2V = UVfsm2 * ( 1. + sigmaJ )**2 + UCLnu2 * sigmaJ**2
UN2V = UN2V + UJD2 + UNfsm2
c
UT2V = UVfsm2 * ( 2. - Gamma + sigmat )**2
UT2V = UT2V + UCLnu2 * ( Gamma - sigmat )**2
UT2V = UT2V + UroS2 + Utd2 + UTfsm2
c
UQ2V = UVfsm2 * ( 2. - Gamma + sigmeta - sigmaJ )**2
UQ2V = UQ2V + UCLnu2 * ( Gamma - sigmeta + sigmaJ )**2
UQ2V = UQ2V + UroS2 + Ueta2 + UJD2 + UQfsm2
c
UP2V = UVfsm2 * ( 3. - Gamma + sigmeta )**2
UP2V = UP2V + UCLnu2 * ( Gamma - sigmeta )**2
UP2V = UP2V + UroS2 + Ueta2 + UPfsm2
c
UE2V = UVfsm2 * ( 3. - Gamma )**2 + UCLnu2 * Gamma**2 + UroS2
c
UVV = 100. * UVfsm
UNV = 100. * SQRT( UN2V )
UTV = 100. * SQRT( UT2V )
UQV = 100. * SQRT( UQ2V )
UPV = 100. * SQRT( UP2V )
UEV = 100. * SQRT( UE2V )
UAV = 20. * SQRT( UVfsm2 + UN2V + UT2V + UQ2V + UP2V )
c
c FULL-SCALE UNCERTAINTIES @ a GIVEN rpm
c

```

UV2N = UNfsm2 + UCLnu2 * sigmaJ**2 + UJD2
UV2N = UV2N / (1. + sigmaJ)**2 + UVfsm2

c

UT2N = (UNfsm2 + UJD2) * (2. - Gamma + sigmat)**2
UT2N = UT2N + UCLnu2 * (Gamma - sigmat + 2. * sigmaJ)**2
UT2N = UT2N / (1. + sigmaJ)**2 + UroS2 + Utd2 + UTfsm2

c

UQ2N = UNfsm2 * (2. - Gamma + sigmeta - sigmaJ)**2
UQ2N = UQ2N + UCLnu2 * (Gamma - sigmeta + 3. * sigmaJ)**2
UQ2N = UQ2N + UJD2 * (3. - Gamma + sigmeta)**2
UQ2N = UQ2N / (1. + sigmaJ)**2 + UroS2 + Ueta2 + UQfsm2

c

UP2N = (UNfsm2 + UJD2) * (3. - Gamma + sigmeta)**2
UP2N = UP2N + UCLnu2 * (Gamma - sigmeta + 3. * sigmaJ)**2
UP2N = UP2N / (1. + sigmaJ)**2 + UroS2 + Ueta2 + UPfsm2

c

UE2N = (UNfsm2 + UJD2) * (3. - Gamma)**2
UE2N = UE2N + UCLnu2 * (Gamma + 3. * sigmaJ)**2
UE2N = UE2N / (1. + sigmaJ)**2 + UroS2

c

UNN = 100. * UNfsm
UVN = 100. * SQRT(UV2N)
UTN = 100. * SQRT(UT2N)
UQN = 100. * SQRT(UQ2N)
UPN = 100. * SQRT(UP2N)
UEN = 100. * SQRT(UE2N)
UAN = 20. * SQRT(UV2N + UNfsm2 + UT2N + UQ2N + UP2N)

c

c FULL-SCALE UNCERTAINTIES @ a GIVEN THRUST

c

UV2T = UTfsm2 + UCLnu2 * (Gamma - sigmat)**2 + UroS2 + Utd2
UV2T = UV2T / (2. - Gamma + sigmat)**2 + UVfsm2

c

UN2T = (UTfsm2 + UroS2 + Utd2) * (1. + sigmaJ)**2
UN2T = UN2T + UCLnu2 * (Gamma - sigmat + 2. * sigmaJ)**2
UN2T = UN2T / (2. - Gamma + sigmat)**2 + UJD2 + UNfsm2

c

UQ2T = (UTfsm2 + Utd2) * (2. - Gamma + sigmeta - sigmaJ)**2
UQ2T = UQ2T + (4. * UCLnu2 + UroS2) * (sigmat - sigmeta + sigmaJ)**2
UQ2T = UQ2T / (2. - Gamma + sigmat)**2 + UJD2 + Ueta2 + UQfsm2

c

UP2T = (UTfsm2 + Utd2) * (3. - Gamma + sigmeta)**2
UP2T = UP2T + UCLnu2 * (Gamma + 2. * sigmeta - 3. * sigmat)**2
UP2T = UP2T + UroS2 * (1. + sigmeta - sigmat)**2
UP2T = UP2T / (2. - Gamma + sigmat)**2 + Ueta2 + UPfsm2

c

$UE2T = (UTfsm2 + Utd2) * (3. - \text{Gamma})^{**2}$
 $UE2T = UE2T + UCLnu2 * (\text{Gamma} - 3. * \text{sigmat})^{**2}$
 $UE2T = UE2T + UroS2 * (1. - \text{sigmat})^{**2}$
 $UE2T = UE2T / (2. - \text{Gamma} + \text{sigmat})^{**2}$

c

$UTT = 100. * UTfsm$
 $UVT = 100. * \text{SQRT}(UV2T)$
 $UNT = 100. * \text{SQRT}(UN2T)$
 $UQT = 100. * \text{SQRT}(UQ2T)$
 $UPT = 100. * \text{SQRT}(UP2T)$
 $UET = 100. * \text{SQRT}(UE2T)$
 $UAT = 20. * \text{SQRT}(UV2T + UN2T + UTfsm2 + UQ2T + UP2T)$

c

FULL-SCALE UNCERTAINTIES @ a GIVEN TORQUE

c

$UV2Q = UQfsm2 + UCLnu2 * (\text{Gamma} - \text{sigmeta} + \text{sigmaJ})^{**2}$
 $UV2Q = UV2Q + UroS2 + Ueta2 + UJD2$
 $UV2Q = UV2Q / (2. - \text{Gamma} + \text{sigmeta} - \text{sigmaJ})^{**2} + UVfsm2$

c

$UN2Q = (UQfsm2 + UroS2 + Ueta2) * (1. + \text{sigmaJ})^{**2}$
 $UN2Q = UN2Q + UCLnu2 * (\text{Gamma} - \text{sigmeta} + 3. * \text{sigmaJ})^{**2}$
 $UN2Q = UN2Q + UJD2 * (3. - \text{Gamma} + \text{sigmeta})^{**2}$
 $UN2Q = UN2Q / (2. - \text{Gamma} + \text{sigmeta} - \text{sigmaJ})^{**2} + UNfsm2$

c

$UT2Q = (UQfsm2 + Ueta2 + UJD2) * (2. - \text{Gamma} + \text{sigmat})^{**2}$
 $UT2Q = UT2Q + (4. * UCLnu2 + UroS2) * (\text{sigmat} - \text{sigmeta} + \text{sigmaJ})^{**2}$
 $UT2Q = UT2Q / (2. - \text{Gamma} + \text{sigmeta} - \text{sigmaJ})^{**2} + Utd2 + UTfsm2$

c

$UP2Q = (UQfsm2 + UJD2) * (3. - \text{Gamma} + \text{sigmeta})^{**2}$
 $UP2Q = UP2Q + UCLnu2 * (\text{Gamma} - \text{sigmeta} + 3. * \text{sigmaJ})^{**2}$
 $UP2Q = UP2Q + (UroS2 + Ueta2) * (1. + \text{sigmaJ})^{**2}$
 $UP2Q = UP2Q / (2. - \text{Gamma} + \text{sigmeta} - \text{sigmaJ})^{**2} + UPfsm2$

c

$UE2Q = (UQfsm2 + UJD2) * (3. - \text{Gamma})^{**2}$
 $UE2Q = UE2Q + UCLnu2 * (\text{Gamma} + 3. * \text{sigmaJ})^{**2}$
 $UE2Q = UE2Q + UroS2 * (1. + \text{sigmaJ})^{**2}$
 $UE2Q = UE2Q / (2. - \text{Gamma} - \text{sigmaJ})^{**2}$

c

$UQQ = 100. * UQfsm$
 $UVQ = 100. * \text{SQRT}(UV2Q)$
 $UNQ = 100. * \text{SQRT}(UN2Q)$
 $UTQ = 100. * \text{SQRT}(UT2Q)$
 $UPQ = 100. * \text{SQRT}(UP2Q)$
 $UEQ = 100. * \text{SQRT}(UE2Q)$
 $UAQ = 20. * \text{SQRT}(UV2Q + UN2Q + UT2Q + UQfsm2 + UP2Q)$

c

c FULL-SCALE UNCERTAINTIES @ a GIVEN SHAFT HORSEPOWER

c
UV2P = UPfsm2 + UCLnu2 * (Gamma-sigmeta)**2 + UroS2 + Ueta2
UV2P = UV2P / (3. - Gamma + sigmeta)**2 + UVfsm2

c
UN2P = (UPfsm2 + UroS2 + Ueta2) * (1. + sigmaJ)**2
UN2P = UN2P + UCLnu2 * (Gamma - sigmeta + 3. * sigmaJ)**2
UN2P = UN2P / (3. - Gamma + sigmeta)**2 + UJD2 + UNfsm2

c
UT2P = (UPfsm2 + Ueta2) * (2. - Gamma + sigmat)**2
UT2P = UT2P + UCLnu2 * (Gamma+2.*sigmeta-3.*sigmat)**2
UT2P = UT2P + UroS2 * (1. + sigmeta - sigmat)**2
UT2P = UT2P / (3. - Gamma + sigmeta)**2 + Utd2 + UTfsm2

c
UQ2P = UPfsm2 * (2. - Gamma + sigmeta - sigmaJ)**2
UQ2P = UQ2P + UCLnu2 * (Gamma - sigmeta + 3. * sigmaJ)**2
UQ2P = UQ2P + (UroS2 + Ueta2) * (1. + sigmaJ)**2
UQ2P = UQ2P / (3. - Gamma + sigmeta)**2 + UJD2 + UQfsm2

c
UE2P = (UPfsm2 + Ueta2) * (3. - Gamma)**2
UE2P = UE2P + (9. * UCLnu2 + UroS2) * sigmeta**2
UE2P = UE2P / (3. - Gamma + sigmeta)**2

c
UPP = 100. * UPfsm
UVP = 100. * SQRT(UV2P)
UNP = 100. * SQRT(UN2P)
UTP = 100. * SQRT(UT2P)
UQP = 100. * SQRT(UQ2P)
UEP = 100. * SQRT(UE2P)
UAP = 20. * SQRT(UV2P + UN2P + UT2P + UQ2P + UPfsm2)

c WRITE INPUT VARIABLES & OUTPUT RESULTS

c Express relative uncertainties in percent

c
Uro = 100. * Uro
Unu = 100. * Unu

c
UL = 100. * UL
US = 100. * US
UD = 100. * UD

c
URTCR = 100. * URTCR
UV = 100. * UV
URT = 100. * URT
UDelR = 100. * UDelR

```

c
  Un = 100. * Un
  UT = 100. * UT
  UQ = 100. * UQ

c
  Uros = 100. * Uros
  Unus = 100. * Unus

c
  ULS = 100. * ULS
  USS = 100. * USS
  UDS = 100. * UDS

c
  UVfsm = 100. * UVfsm
  UNfsm = 100. * UNfsm
  UTfsm = 100. * UTfsm
  UQfsm = 100. * UQfsm
  UPfsm = 100. * UPfsm

c
  UCA = 100. * dCA / CA

c
  open(12,file='UA3.out',status='new')

c
  write(12,*) TTxp
  write(12,*) date
  write(12,*) model
  write(12,*) prop
  write(12,*) EHPxp
  write(12,*) SHPxp
  write(12,*) comment

c
  write(12,*)
  write(12,*) ' INPUT VARIABLES'
  write(12,*)

c
  write(12,*)
  write(12,*) ' TANK-WATER PROPERTIES'
  write(12,*)
  write(12,101) ro
  write(12,102) nu
  write(12,103) Uro
  write(12,104) Unu

c
  write(12,*)
  write(12,*) ' MODEL GEOMETRY'
  write(12,*)
  write(12,105) L

```

```

write(12,106) S
write(12,107) D
write(12,108) UL
write(12,109) US
write(12,110) UD
c
write(12,*)
write(12,*)' MODEL-SCALE VARIABLES : RESISTANCE TESTS'
write(12,*)
write(12,111) VCRknot
write(12,112) RTCR
write(12,113) URTCR
c
write(12,*)
write(12,*)' MODEL-SCALE VARIABLES : PROPULSION TESTS'
write(12,*)
write(12,114) Vknot
write(12,115) RT
write(12,116) DelR
write(12,117) nrpm
write(12,118) T
write(12,119) Qinlb
c
write(12,*)
write(12,*)' UNCERTAINTIES OF MODEL-SCALE MEASUREMENTS'
write(12,*)
write(12,120) UV
write(12,121) URT
write(12,122) UDeIR
write(12,123) Un
write(12,124) UT
write(12,125) UQ
c
write(12,*)
write(12,*)' OTHER MODEL-SCALE VARIABLES'
write(12,*)
write(12,126) JVCT
write(12,127) tdCT
write(12,128) etaCT
c
write(12,*)
write(12,*)' SEA-WATER PROPERTIES'
write(12,*)
write(12,151) nusea
write(12,152) Uros
write(12,153) Unus

```

```

c
write(12,*)
write(12,*) ' FULL-SCALE SHIP'
write(12,*)
write(12,154) LS
write(12,155) VSknut
write(12,156) ULS
write(12,157) USS
write(12,158) UDS

c
write(12,*)
write(12,*) ' UNCERTAINTIES OF FULL-SCALE MEASUREMENTS'
write(12,*)
write(12,159) UVfsm
write(12,160) UNfsm
write(12,161) UTfsm
write(12,162) UQfsm
write(12,163) UPfsm

c
write(12,*)
write(12,*) ' SCALING ALLOWANCE'
write(12,*)
write(12,171) CA
write(12,172) dCA

c
write(12,*)
write(12,*)
write(12,*) ' OUTPUT VARIABLES'
write(12,*)

c
write(12,*)
write(12,*) ' MODEL-SCALE VARIABLES : RESISTANCE TESTS'
write(12,*)
write(12,201) CTCR
write(12,202) CFCR
write(12,203) CR

c
write(12,*)
write(12,*) ' MODEL-SCALE VARIABLES : PROPULSION TESTS'
write(12,*)
write(12,204) CT
write(12,205) CF
write(12,206) CR
write(12,*)
write(12,207) JV
write(12,208) td

```

```

write(12,209) eta
c
write(12,*)
write(12,*) ' UNCERTAINTIES OF MODEL-SCALE VARIABLES :
RESISTANCE TESTS'
write(12,*)
write(12,210) UCTCR
write(12,211) UCFCR
write(12,212) UCR
c
write(12,*)
write(12,*) ' UNCERTAINTIES OF MODEL-SCALE VARIABLES :
PROPULSION TESTS'
write(12,*)
write(12,213) UCT
write(12,214) UCF
write(12,215) UCR
write(12,216) UCA
write(12,*)
write(12,217) UJV
write(12,218) Utd
write(12,219) Ueta
c
write(12,*)
write(12,*) ' FULL-SCALE VARIABLES'
write(12,*)
write(12,220) CTS
write(12,221) CFS
write(12,222) CR
write(12,223) CA
c
write(12,*)
write(12,*) ' UNCERTAINTIES of FULL-SCALE PREDICTIONS at a GIVEN
SPEED'
write(12,*)
write(12,311) UVV
write(12,312) UNV
write(12,313) UTV
write(12,314) UQV
write(12,315) UPV
write(12,316) UEV
write(12,317) UAV
c
write(12,*)
write(12,*) ' UNCERTAINTIES of FULL-SCALE PREDICTIONS at a GIVEN
rpm'

```

```
write(12,*)
write(12,321) UVN
write(12,322) UNN
write(12,323) UTN
write(12,324) UQN
write(12,325) UPN
write(12,326) UEN
write(12,327) UAN
```

c

```
write(12,*)
write(12,*)'UNCERTAINTIES of FULL-SCALE PREDICTIONS at a GIVEN
THRUST'
write(12,*)
write(12,331) UVT
write(12,332) UNT
write(12,333) UTT
write(12,334) UQT
write(12,335) UPT
write(12,336) UET
write(12,337) UAT
```

c

```
write(12,*)
write(12,*)'UNCERTAINTIES of FULL-SCALE PREDICTIONS at a GIVEN
TORQUE'
write(12,*)
write(12,341) UVQ
write(12,342) UNQ
write(12,343) UTQ
write(12,344) UQQ
write(12,345) UPQ
write(12,346) UEQ
write(12,347) UAQ
```

c

```
write(12,*)
write(12,*)'UNCERTAINTIES of FULL-SCALE PREDICTIONS at a GIVEN
SHP'
write(12,*)
write(12,351) UVP
write(12,352) UNP
write(12,353) UTP
write(12,354) UQP
write(12,355) UPP
write(12,356) UEP
write(12,357) UAP
```

c

```
close(12,status='keep')
```

```

c
c      FORMATS
c
101 format(' water density (slug/ft**3) :      ',F11.3)
102 format(' kinematic viscosity coefficient (ft**2/sec) : ',E11.4)
103 format(' percent uncertainty of density : ',F8.2)
104 format(' percent uncertainty of viscosity : ',F8.2)
c
105 format(' length of model (ft) :      ',F8.3)
106 format(' wetted area (ft**2) :      ',F8.3)
107 format(' diameter of propeller (ft) : ',F8.4)
108 format(' percent uncertainty of length :      ',F8.2)
109 format(' percent uncertainty of wetted surface : ',F8.2)
110 format(' percent uncertainty of prop diameter : ',F8.2)
c
111 format(' carriage speed (knots) :      ',F8.2)
112 format(' drag (lbs) :      ',F8.2)
113 format(' percent uncertainty of drag :      ',F8.2)
c
114 format(' carriage speed (knots) : ',F8.2)
115 format(' drag RT (lbs) :      ',F8.2)
116 format(' drag DeltaR (lbs) :      ',F8.2)
117 format(' propeller rpm :      ',F8.2)
118 format(' propeller thrust (lbs) : ',F8.2)
119 format(' propeller torque (in-lbs) : ',F8.2)
c
120 format(' percent uncertainty of model speed : ',F8.2)
121 format(' percent uncertainty of drag RT :      ',F8.2)
122 format(' percent uncertainty of drag DeltaR : ',F8.2)
123 format(' percent uncertainty of propeller rpm : ',F8.2)
124 format(' percent uncertainty of prop thrust : ',F8.2)
125 format(' percent uncertainty of prop torque : ',F8.2)
c
126 format(' slope d JV / d CT : ',F9.3)
127 format(' slope d (1-t) / d CT : ',F9.3)
128 format(' slope d etaD / d CT : ',F9.3)
c
151 format(' kinematic viscosity coefficient (ft**2/sec) : ',E11.4)
152 format(' percent uncertainty of density : ',F8.2)
153 format(' percent uncertainty of viscosity : ',F8.2)
c
154 format(' ship length (ft) :      ',F8.2)
155 format(' ship speed (knots) :      ',F11.1)
c
156 format(' percent uncertainty of ship length : ',F8.2)
157 format(' percent uncertainty of wetted surface : ',F8.2)

```

```

158 format(' percent uncertainty of prop diameter : ',F8.2)
c
159 format(' percent uncertainty of ship speed : ',F8.2)
160 format(' percent uncertainty of prop rpm : ',F8.2)
161 format(' percent uncertainty of prop thrust : ',F8.2)
162 format(' percent uncertainty of prop torque : ',F8.2)
163 format(' percent uncertainty of SHP : ',F8.2)
c
171 format(' correlation allowance : ',F11.5)
172 format(' uncertainty of allowance : ',F11.5)
c
201 format(' total resistance coefficient CT : ',F10.5)
202 format(' friction resistance coefficient CF : ',F10.5)
203 format(' residuary resistance coefficient CR : ',F10.5)
c
204 format(' total resistance coefficient CT : ',F10.5)
205 format(' friction resistance coefficient CF : ',F10.5)
206 format(' residuary resistance coefficient CR : ',F10.5)
c
207 format(' advance ratio JV : ',F8.2)
208 format(' thrust-deduction factor 1-t : ',F8.2)
209 format(' propulsive efficiency etaD : ',F8.2)
c
210 format(' percent uncertainty of CT : ',F8.2)
211 format(' percent uncertainty of CF : ',F8.2)
212 format(' percent uncertainty of CR : ',F8.2)
c
213 format(' percent uncertainty of CT : ',F8.2)
214 format(' percent uncertainty of CF : ',F8.2)
215 format(' percent uncertainty of CR : ',F8.2)
216 format(' percent uncertainty of CA : ',F8.2)
c
217 format(' percent uncertainty of JV : ',F8.2)
218 format(' percent uncertainty of 1-t : ',F8.2)
219 format(' percent uncertainty of etaD : ',F8.2)
c
220 format(' total resistance coefficient CT : ',F10.5)
221 format(' friction resistance coefficient CF : ',F10.5)
222 format(' residuary resistance coefficient CR : ',F10.5)
223 format(' correlation allowance coefficient CA : ',F10.5)
c
311 format(' percent uncertainty of ship speed : ',F8.2)
312 format(' percent uncertainty of prop rpm : ',F8.2)
313 format(' percent uncertainty of prop thrust : ',F8.2)
314 format(' percent uncertainty of prop torque : ',F8.2)
315 format(' percent uncertainty of SHP : ',F8.2)

```

```

316 format(' percent uncertainty of EHP :      ',F8.2)
317 format(' percent overall uncertainty :      ',F8.2)
c
321 format(' percent uncertainty of ship speed : ',F8.2)
322 format(' percent uncertainty of prop rpm :  ',F8.2)
323 format(' percent uncertainty of prop thrust : ',F8.2)
324 format(' percent uncertainty of prop torque : ',F8.2)
325 format(' percent uncertainty of SHP :        ',F8.2)
326 format(' percent uncertainty of EHP :        ',F8.2)
327 format(' percent overall uncertainty :      ',F8.2)
c
331 format(' percent uncertainty of ship speed : ',F8.2)
332 format(' percent uncertainty of prop rpm :  ',F8.2)
333 format(' percent uncertainty of prop thrust : ',F8.2)
334 format(' percent uncertainty of prop torque : ',F8.2)
335 format(' percent uncertainty of SHP :        ',F8.2)
336 format(' percent uncertainty of EHP :        ',F8.2)
337 format(' percent overall uncertainty :      ',F8.2)
c
341 format(' percent uncertainty of ship speed : ',F8.2)
342 format(' percent uncertainty of prop rpm :  ',F8.2)
343 format(' percent uncertainty of prop thrust : ',F8.2)
344 format(' percent uncertainty of prop torque : ',F8.2)
345 format(' percent uncertainty of SHP :        ',F8.2)
346 format(' percent uncertainty of EHP :        ',F8.2)
347 format(' percent overall uncertainty :      ',F8.2)
c
351 format(' percent uncertainty of ship speed : ',F8.2)
352 format(' percent uncertainty of prop rpm :  ',F8.2)
353 format(' percent uncertainty of prop thrust : ',F8.2)
354 format(' percent uncertainty of prop torque : ',F8.2)
355 format(' percent uncertainty of SHP :        ',F8.2)
356 format(' percent uncertainty of EHP :        ',F8.2)
357 format(' percent overall uncertainty :      ',F8.2)
c
    stop
c
    end

```

EXAMPLE INPUT FILE

' TOW-TANK EXP '
' DATE: XXXX '
' MODEL No. XXXX '
' PROPELLER No. XXXX '
' EHP EXPERIMENT No. XXXX '
' SHP EXPERIMENT No. XXXX '
' COMMENTS: CASE MFC '

MODEL-SCALE VARIABLES AND UNCERTAINTIES

Tank-water density (rho) and kinematic viscosity (nu)
rho (slug/ft**3) nu X 10**5 (ft**2/sec)
1.9367 , 1.084

Percent relative uncertainties of rho & nu
density kinematic viscosity
0.07 , 2.1

Model geometry
length (ft) area (ft**2) prop diameter (ft)
22.697 , 138.179 , 0.9986

Percent relative uncertainties of model geometry
length area prop diameter
0.14 , 0.71 , 0.071

RESISTANCE (EHP) TESTS

speed (knots) drag (lbs)
6.0 , 46.66

Percent relative uncertainty of drag
1.7

PROPULSION TESTS

speed (knots) RT (lbs) DeltaR
18.0 , 392.64 , 70.1

rpm thrust (lbs) torque (in-lbs)
923.4 , 551.0 , 1501.0

Percent relative uncertainties
speed RT DeltaR rpm thrust torque
0.21 , 1.7 , 1.7 , 0.42 , 0.71 , 0.71

Other model variables : slopes of 1-t , JV & etaD versus CT

dJV/dCT	d(1-t)/dCT	dataD/dCT
-0.249 ,	0.067 ,	-0.015

FULL-SCALE VARIABLES AND UNCERTAINTIES

Sea-water kinematic viscosity

$\nu \times 10^{*5}$ (ft**2/sec)

1.282

Percent relative uncertainties of sea-water properties

density kinematic viscosity

1.0 ,	2.0
-------	-----

Full-scale variables

ship length (ft) ship speed (knots)

380.0 ,	25.0
---------	------

Percent relative uncertainties of full-scale geometry

length area prop diameter

0.5 ,	1.0 ,	0.1
-------	-------	-----

Percent relative uncertainties of full-scale measurements

speed rpm thrust torque SHP

0.6 ,	0.4 ,	3.0 ,	0.9 ,	0.9
-------	-------	-------	-------	-----

SCALING ALLOWANCE

CA dCA

0.0005 ,	0.0001
----------	--------

EXAMPLE OUTPUT FILE

TOW-TANK EXP

DATE: XXXX

MODEL No. XXXX

PROPELLER No. XXXX

EHP EXPERIMENT No. XXXX

SHP EXPERIMENT No. XXXX

COMMENTS: CASE MFC

INPUT VARIABLES

TANK-WATER PROPERTIES

water density (slug/ft^{**3}) : 1.937
kinematic viscosity coefficient (ft^{**2}/sec) : 0.1084E-04
percent uncertainty of density : 0.07
percent uncertainty of viscosity : 2.10

MODEL GEOMETRY

length of model (ft) : 22.697
wetted area (ft^{**2}) : 138.179
diameter of propeller (ft) : 0.9986
percent uncertainty of length : 0.14
percent uncertainty of wetted surface : 0.71
percent uncertainty of prop diameter : 0.07

MODEL-SCALE VARIABLES : RESISTANCE TESTS

carriage speed (knots) : 6.00
drag (lbs) : 46.66
percent uncertainty of drag : 1.70

MODEL-SCALE VARIABLES : PROPULSION TESTS

carriage speed (knots) : 18.00
drag RT (lbs) : 392.64
drag DeltaR (lbs) : 70.10
propeller rpm : 923.40
propeller thrust (lbs) : 551.00
propeller torque (in-lbs) : 1501.00

UNCERTAINTIES OF MODEL-SCALE MEASUREMENTS

percent uncertainty of model speed : 0.21

percent uncertainty of drag RT : 1.70
percent uncertainty of drag DeltaR : 1.70
percent uncertainty of propeller rpm : 0.42
percent uncertainty of prop thrust : 0.71
percent uncertainty of prop torque : 0.71

OTHER MODEL-SCALE VARIABLES

slope d JV / d CT : -0.249
slope d (1-t) / d CT : 0.067
slope d etaD / d CT : -0.015

SEA-WATER PROPERTIES

kinematic viscosity coefficient (ft**2/sec) : 0.1282E-04
percent uncertainty of density : 1.00
percent uncertainty of viscosity : 2.00

FULL-SCALE SHIP

ship length (ft) : 380.00
ship speed (knots) : 25.0
percent uncertainty of ship length : 0.50
percent uncertainty of wetted surface : 1.00
percent uncertainty of prop diameter : 0.10

UNCERTAINTIES OF FULL-SCALE MEASUREMENTS

percent uncertainty of ship speed : 0.60
percent uncertainty of prop rpm : 0.40
percent uncertainty of prop thrust : 3.00
percent uncertainty of prop torque : 0.90
percent uncertainty of SHP : 0.90

SCALING ALLOWANCE

correlation allowance : 0.00050
uncertainty of allowance : 0.00010

OUTPUT VARIABLES

MODEL-SCALE VARIABLES : RESISTANCE TESTS

total resistance coefficient CT : 0.00340
friction resistance coefficient CF : 0.00264

residuary resistance coefficient CR : 0.00075

MODEL-SCALE VARIABLES : PROPULSION TESTS

total resistance coefficient CT : 0.00261

friction resistance coefficient CF : 0.00223

residuary resistance coefficient CR : 0.00075

advance ratio JV : 1.98

thrust-deduction factor 1-t : 0.59

propulsive efficiency etaD : 0.81

UNCERTAINTIES OF MODEL-SCALE VARIABLES : RESISTANCE TESTS

percent uncertainty of CT : 1.89

percent uncertainty of CF : 0.34

percent uncertainty of CR : 8.58

UNCERTAINTIES OF MODEL-SCALE VARIABLES : PROPULSION TESTS

percent uncertainty of CT : 2.26

percent uncertainty of CF : 0.32

percent uncertainty of CR : 8.58

percent uncertainty of CA : 20.00

percent uncertainty of JV : 0.47

percent uncertainty of 1-t : 2.22

percent uncertainty of etaD : 2.27

FULL-SCALE VARIABLES

total resistance coefficient CT : 0.00274

friction resistance coefficient CF : 0.00149

residuary resistance coefficient CR : 0.00075

correlation allowance coefficient CA : 0.00050

UNCERTAINTIES of FULL-SCALE PREDICTIONS at a GIVEN SPEED

percent uncertainty of ship speed : 0.60

percent uncertainty of prop rpm : 0.87

percent uncertainty of prop thrust : 6.01

percent uncertainty of prop torque : 5.33

percent uncertainty of SHP : 5.47

percent uncertainty of EHP : 4.90

percent overall uncertainty : 1.96

UNCERTAINTIES of FULL-SCALE PREDICTIONS at a GIVEN rpm

percent uncertainty of ship speed : 0.87
percent uncertainty of prop rpm : 0.40
percent uncertainty of prop thrust : 6.02
percent uncertainty of prop torque : 5.42
percent uncertainty of SHP : 5.50
percent uncertainty of EHP : 4.92
percent overall uncertainty : 1.97

UNCERTAINTIES of FULL-SCALE PREDICTIONS at a GIVEN THRUST

percent uncertainty of ship speed : 3.11
percent uncertainty of prop rpm : 3.11
percent uncertainty of prop thrust : 3.00
percent uncertainty of prop torque : 4.48
percent uncertainty of SHP : 6.60
percent uncertainty of EHP : 6.13
percent overall uncertainty : 1.92

UNCERTAINTIES of FULL-SCALE PREDICTIONS at a GIVEN TORQUE

percent uncertainty of ship speed : 2.76
percent uncertainty of prop rpm : 2.80
percent uncertainty of prop thrust : 4.48
percent uncertainty of prop torque : 0.90
percent uncertainty of SHP : 3.19
percent uncertainty of EHP : 2.82
percent overall uncertainty : 1.36

UNCERTAINTIES of FULL-SCALE PREDICTIONS at a GIVEN SHP

percent uncertainty of ship speed : 1.86
percent uncertainty of prop rpm : 1.87
percent uncertainty of prop thrust : 4.35
percent uncertainty of prop torque : 2.10
percent uncertainty of SHP : 0.90
percent uncertainty of EHP : 2.44
percent overall uncertainty : 1.12

APPENDIX D: REPEATABILITY OF MODEL-SCALE MEASUREMENTS

The precision uncertainties associated with submarine model tow-tank testing are investigated by considering two complete tow-tank test series. These two test series are representative of the submarine model resistance and powering experimental evaluations currently being performed in the NSWCCD towing tank. The first test series was performed from 01/2/96 to 2/20/96. The second test series was performed from 5/19/97 to 06/20/97. The current model test speed range of 6-18 knots is represented in these tests, as well as the current data collection instrumentation and calibration techniques.

The precision uncertainties of the model measurements of speed, drag, rpm, thrust, and torque are evaluated two ways. First, the gage calibrations and instrumentation were analyzed for uncertainties. The drag, thrust, and torque gages are calibrated on site and the electronic instrumentation manufacturer specifications are examined. These precision uncertainties are generally very small. A better assessment of the model measurement precision uncertainties is obtained by analyzing the collected test data. This second way of evaluating the measurement precision uncertainties takes into account the whole data collection system, including the effects of changing model conditions during a test series, water flow variations, variation in force gages, instrumentation accuracy, carriage vibrations, and computer collection and recording of the collected model speed, model drag, shaft RPM, shaft thrust and shaft torque values. The methods used to determine the precision uncertainties of the model provide conservative uncertainty values for use in the global uncertainty analysis. The calibration and measurement precision uncertainties for the five main measured model quantities, i.e., model speed and drag, shaft RPM, thrust, and torque, are examined below.

Calibration of the drag, thrust, and torque gages is completed before each test series. These calibrations consist of determining a unit/volt factor which is used for converting from measured volts to physical units. The weights used for the calibration are calibrated every two years to a tolerance of 0.01% of the nominal

weight by the State of Maryland Department of Agriculture Weights and Measures Section. The tolerances are given in Table 2 through 5 of the NIST Handbook 105-1 (Revised 1990), "Class F Tolerances for Field Standards Weights." The uncertainty of a single measurement within a calibration is calculated by first taking two times the standard deviation of the data spots within that calibration. The average of these standard deviations for all the calibrations is calculated next and represents the precision uncertainty of a single measurement in the test series. This also provides verification of the linearity of the calibration factor. The cal factor used for the test is determined by averaging the multiple number of calibrations for each gage. The precision error associated with determining the cal factor is given by two times the standard deviation of the set of averages of the calibrations. Figure D.1. presents calibration examples for drag, thrust, and torque. The instrumentation currently being used for the model test measurements is presented in Table D.1. The calibration precision uncertainty results are presented in Table D.2. and D.3. for two test series.

A typical resistance or powering experiment will consist of a minimum of approximately 20 data spots with each data spot consisting of the average value of 5 seconds of data collection at 400 samples/second for a total sample of 2000 for a set speed, drag, and RPM (for powering) condition.

The precision uncertainty for model speed is calculated using all the speed data from the tests within the two series. Two times the standard deviation of approximately 20 data spots for each test was calculated to determine the precision uncertainty for that particular test. The results are presented in Tables D.4. and D.5. Model speed collected for a typical experiment is presented in Figure D.2.

The precision uncertainty in model drag is calculated by using measured values of drag at the same nominal model speed. A correction is applied to the measured drag to reduce the effects of the speed variation on the measured drag uncertainty. The measured drag is multiplied by $(V_N)^2 / (V_M)^2$, where V_M = measured speed and V_N = nominal speed. EHP tests, before no-loads, and after no-loads are used as the source of the data. This drag data was taken throughout the test series and therefore represents a large data set for the uncertainty analysis. The no-loads

are collected before and after most SHP tests to find the model drag and other forces. No-loads are also a check to ensure that test conditions have not changed. The precision uncertainties are presented in Tables D.6. and D.7. Model drag measurements for a complete test series are presented in Figure D.3.

The precision uncertainties for model thrust, torque, and RPM are determined differently from the model drag and speed uncertainties. Typical submarine powering experiments consist of varying the propeller rpm to produce different submarine loadings. The precision uncertainty for the shaft thrust, torque, and RPM has been estimated by determining the variation of the thrust, torque, and RPM data from a least squares curve fit through the data spots of a test. Each test contains about 20 data spots which comprise a range of thrust, torque and RPM versus total drag coefficient (C_T) values. The thrust, torque, and RPM are plotted against C_T and a second-order least squared curve is fit through each set of data. Twice the standard error estimate of the data set is calculated and taken to be the precision uncertainty for that test. Examples are shown in Figures D.4., D.5., and D.6. The results are presented in Tables D.8. and D.9.

The following table summarizes the precision uncertainties for tow-tank model testing.

U_P speed	U_P drag	U_P thrust	U_P torque	U_P rpm
0.15%	1.2%	0.5%	0.5%	0.3%

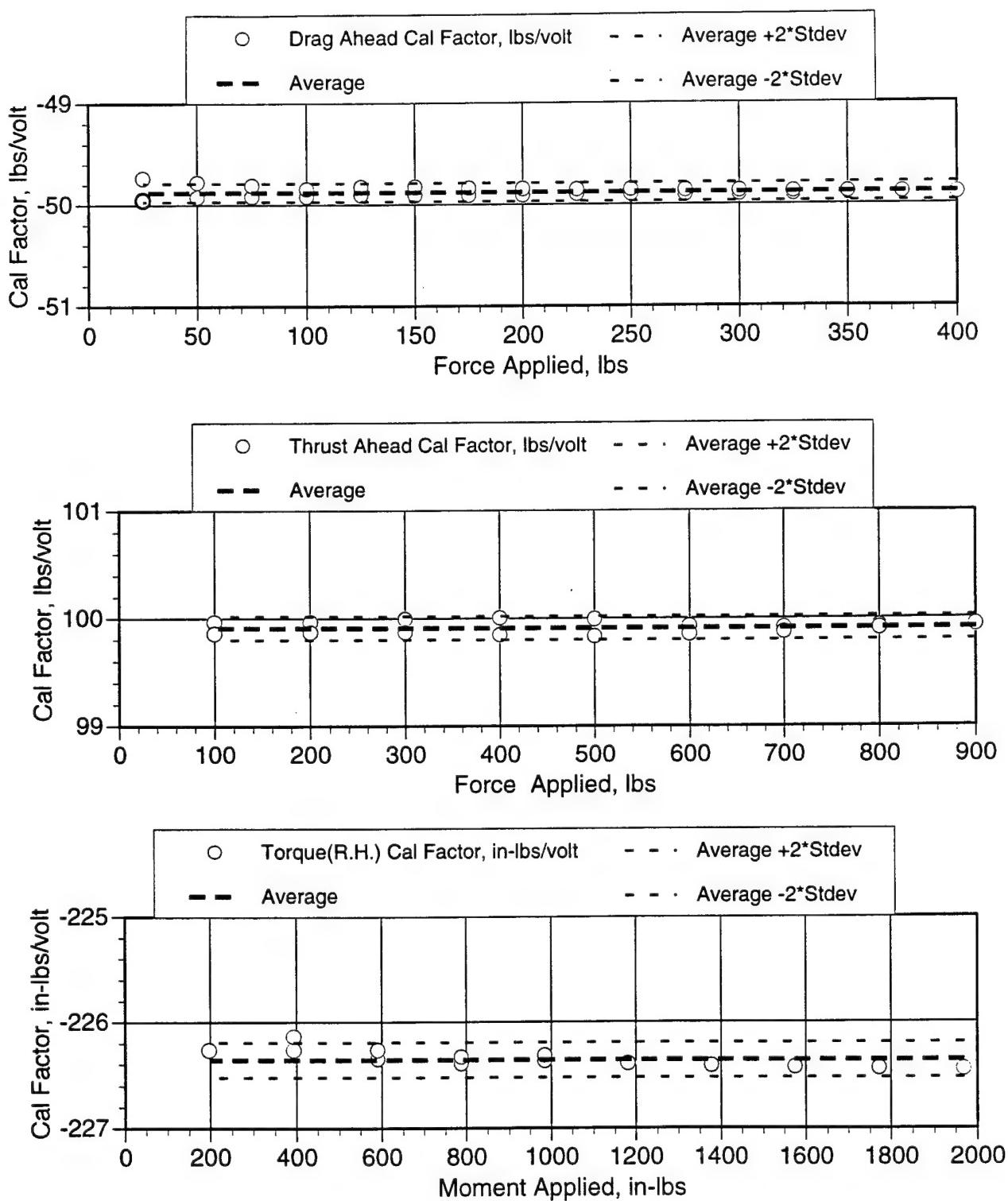


Fig. D.1. Examples of calibration measurements and uncertainty for model drag, thrust, and torque

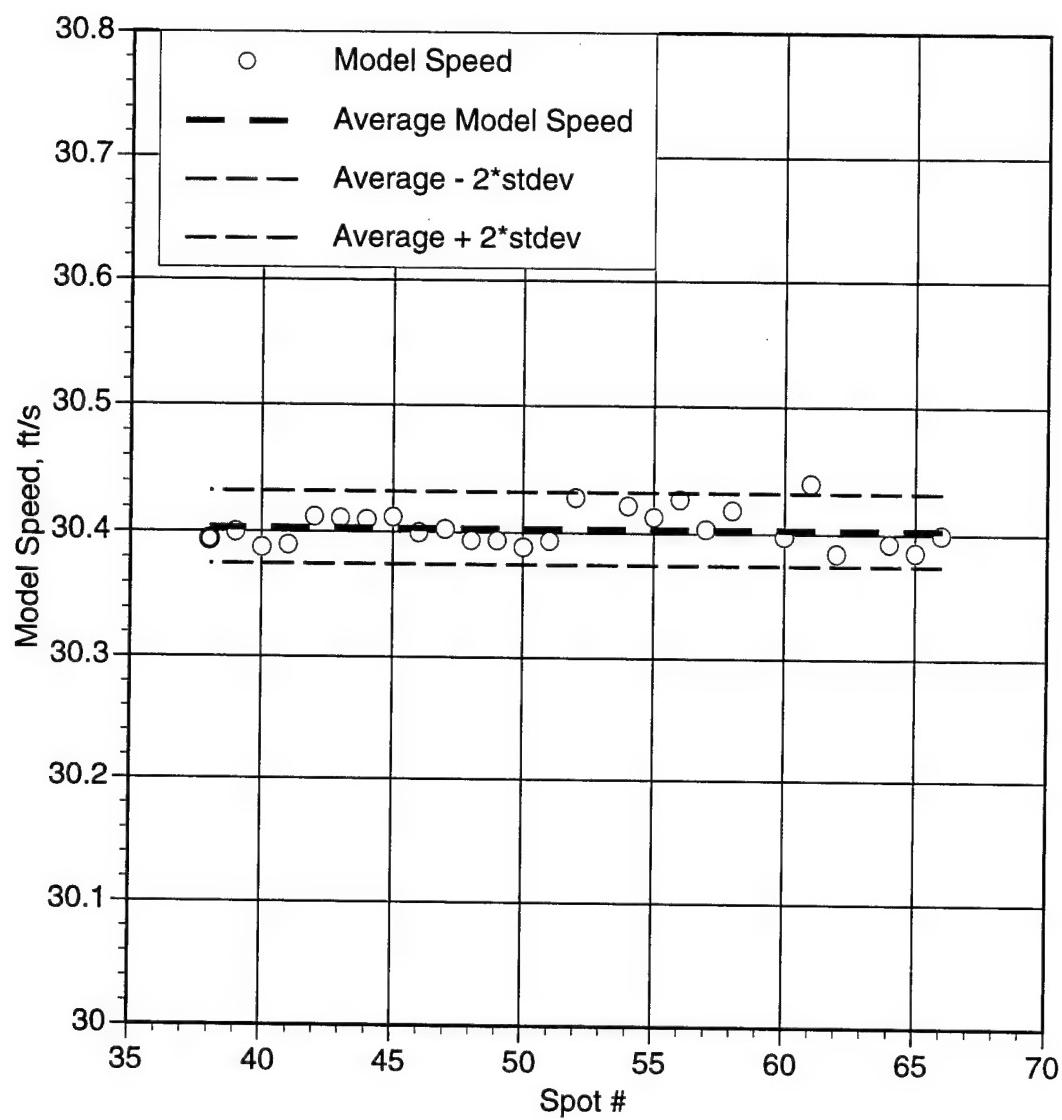


Fig. D.2. Example of model speed measurements and uncertainty for one experiment

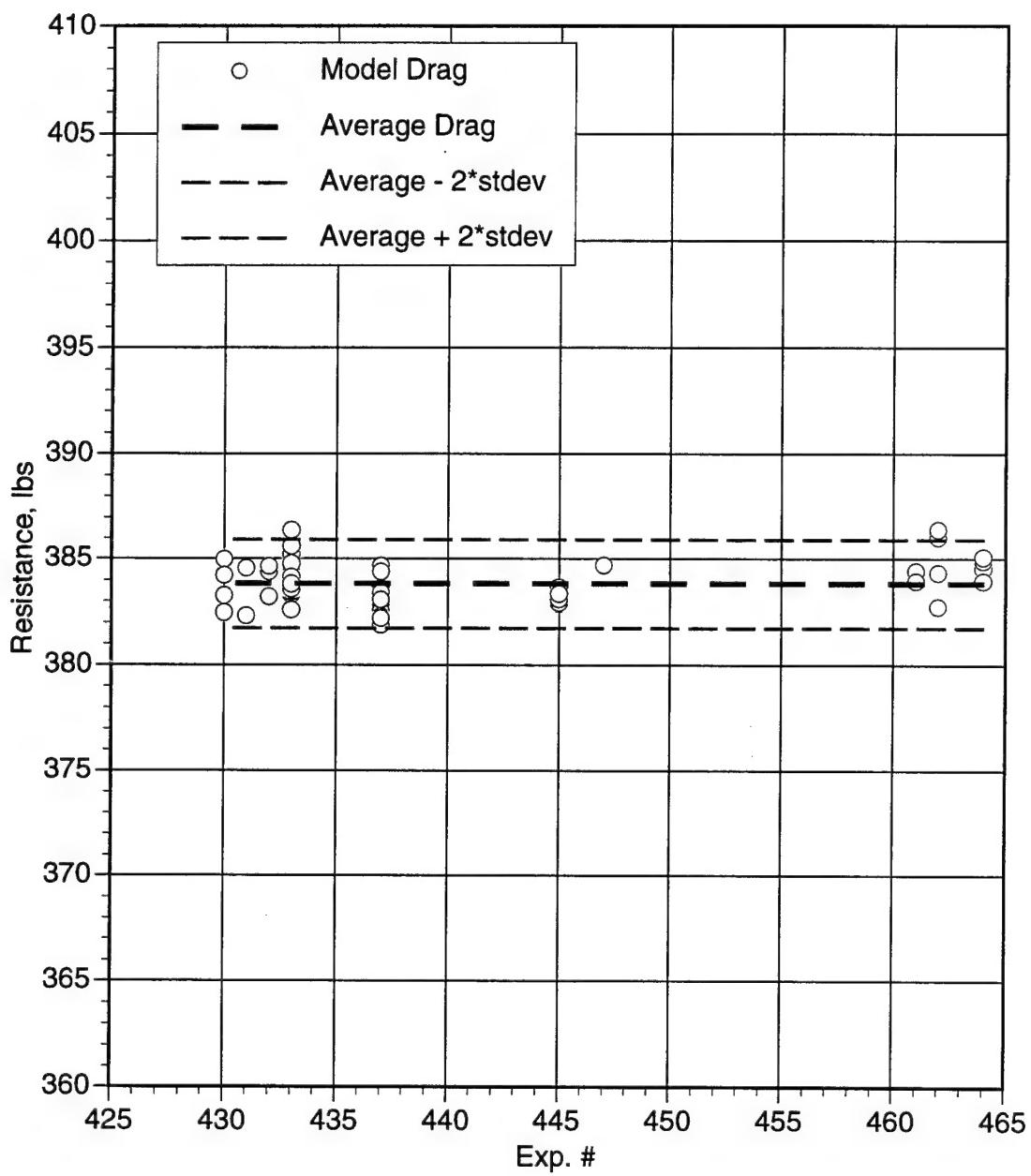


Fig. D.3. Example of model drag measurements and uncertainty for a complete test series

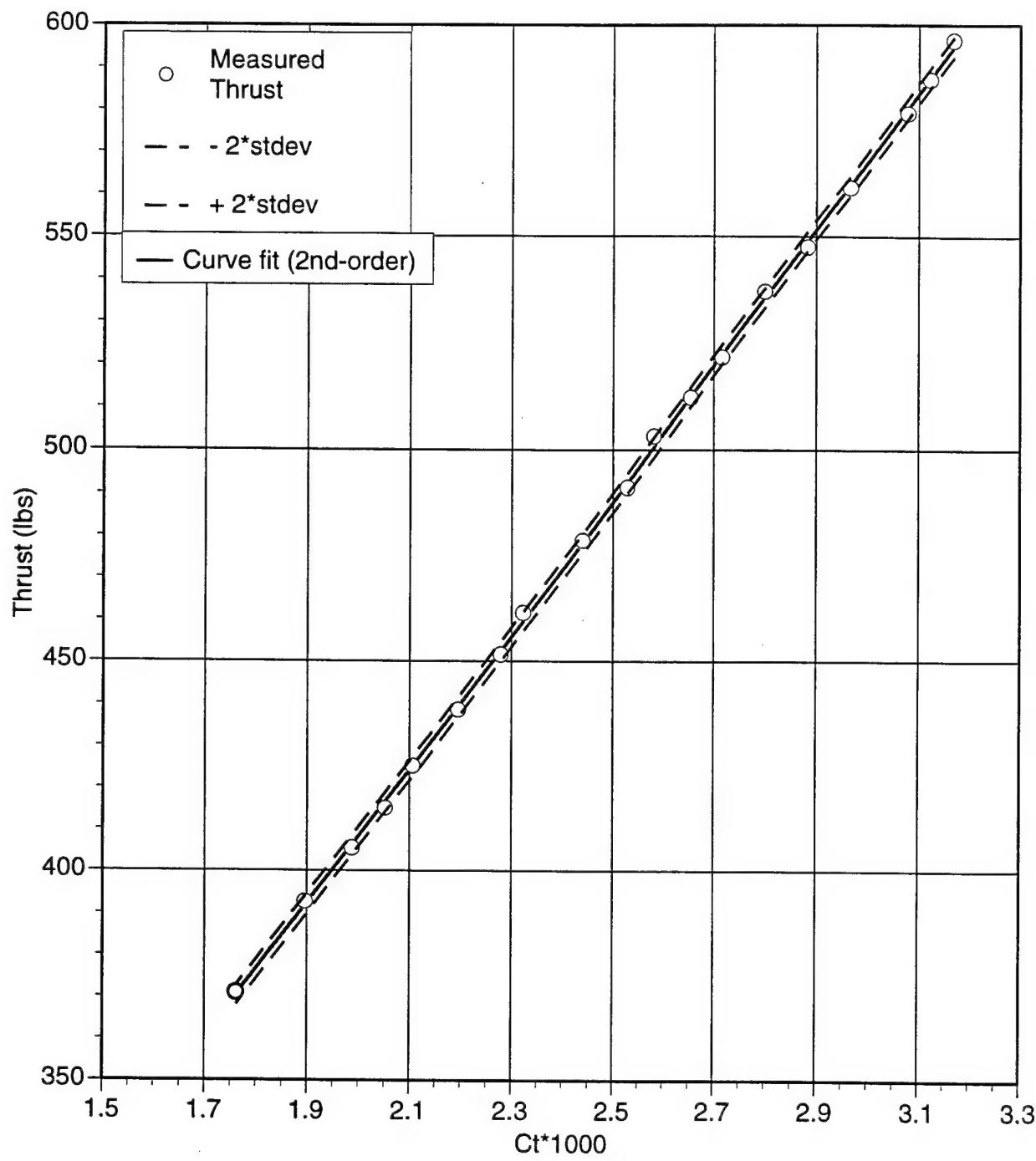


Fig. D.4. Example of model thrust measurements and uncertainty from one experiment

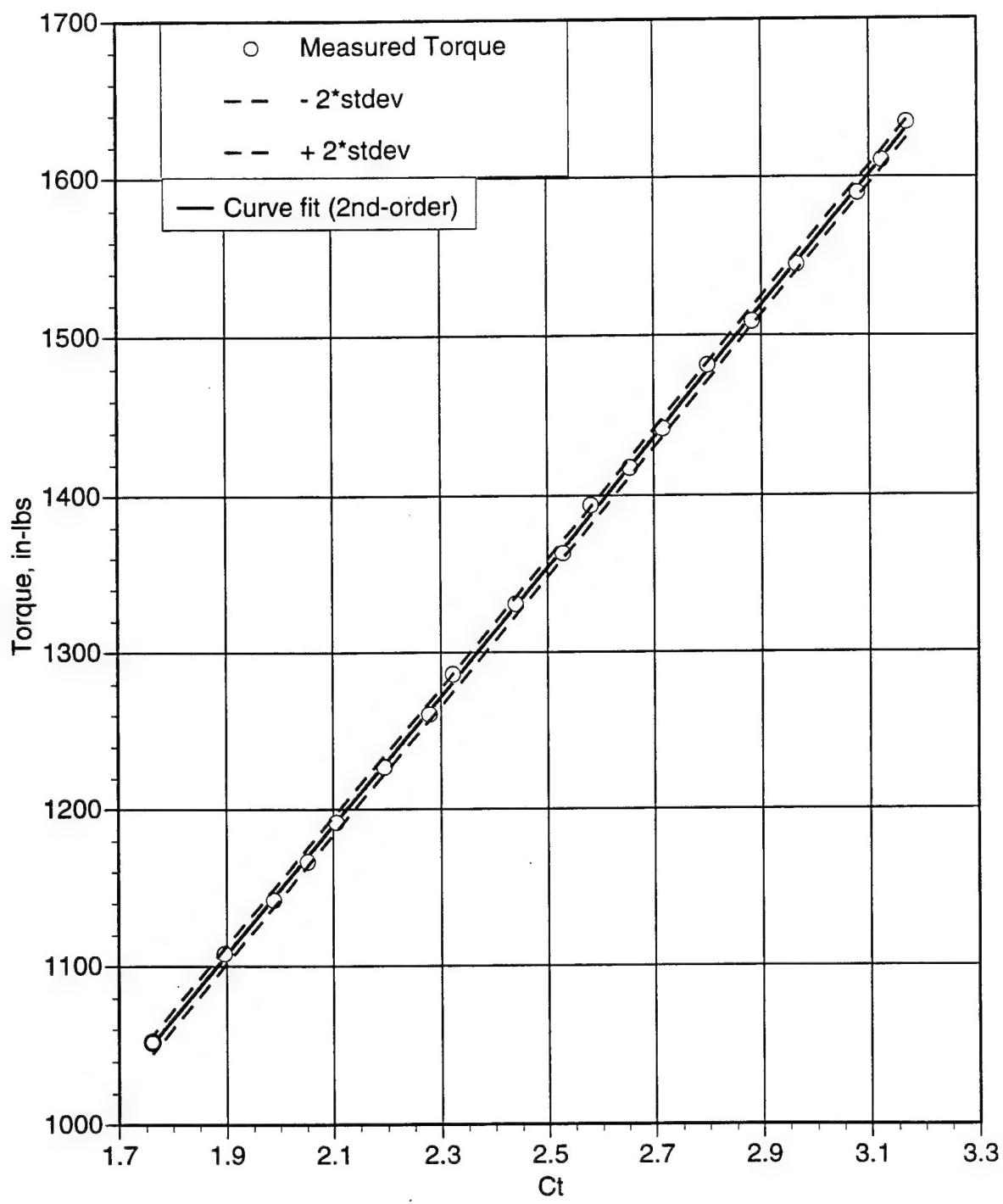


Fig. D.5. Example of model torque measurements and uncertainty from one experiment

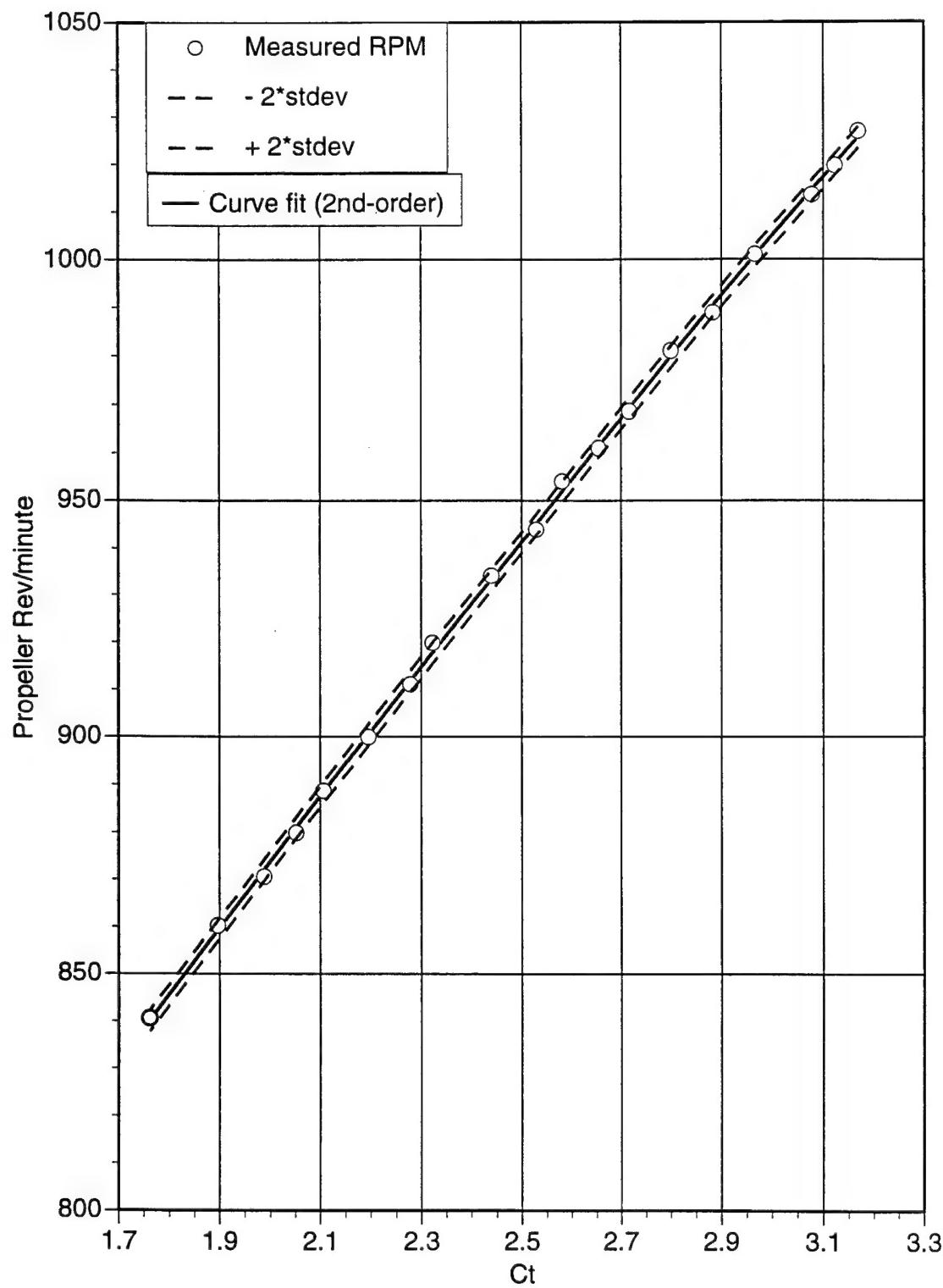


Fig. D.6. Example of model RPM measurements and uncertainty from one experiment

Table D.1. Instrumentation used for the two resistance and powering tests

INSTRUMENT		
Carriage Speed (same as model speed)	Type	magnetic pick-up to counter
	Manufacturer	Airpax
	Model	Zero-Velocity Pickup
	Wheel	520-tooth
	Counter	Hewlett Packard
	Counter Model	5316B
RPM	Type	magnetic pick-up to counter
	Manufacturer	Airpax
	Model	Zero-Velocity Pickup
	Wheel	60-tooth
	Counter	Hewlett Packard
	Counter Model	5316B
Drag Dynamometer	Manufacturer	NSWCCD
	Model	high speed 500 lb
	Type	full bridge strain gauge type
	Max drag force	500 lb
	Max lift force	500 lb
	Max side force	500 lb
	Max pitching moment	3200 ft-lbs
	Max yawing moment	3200 ft-lbs
Thrust and Torque Dynamometer	Manufacturer	Kempf & Remmers
	Model	R 58
	Type	full bridge strain gauge type
	Rated thrust	+/- 1000 lb
	Rated torque	+/- 150 lb-ft
	Max rpm in water	3600 rpm
	Overload T&Q allowed	30%
Signal Conditioner (used with drag, thrust, and torque gage)	Manufacturer	Vishay
	Model	2310
Differential DC Amplifier (used with drag, thrust, torque, rpm and speed)	Manufacturer	Ectron
	Model	751ELN

Table D.2. Calibration uncertainty for the model drag, shaft thrust, and shaft torque gages for the first resistance and powering test series.

Drag (ahead)		Cal #1 0-400 lb, by 25 lb increment 31	Cal #2 0-100 lb, by 10 lb increment 31	Cal #3 0-100 lb, by 10 lb increment 19	Cal #4 0-100 lb, by 10 lb increment 19	Averages	2*StdDev(%) of Average Cal Factors 0.06%
Range	# of spots	-49.4803	-49.4373	-49.4605	-49.4612	-49.4598	
Average Cal Factor (lb/volt)	2*StdDev (%)	0.27%	0.22%	0.11%	0.14%	0.18%	

Thrust (ahead)		Cal #1 0-900 lb, by 100 lb increment 17	Cal #2 0-100 lb increment 17	Cal #3 0-100 lb increment 99.9016	Cal #4 0-100 lb increment 99.9036	Averages	2*StdDev(%) of Average Cal Factors n/a
Range	# of spots	99.9056	99.9016	99.9036	99.9036	99.9036	
Average Cal Factor (lb/volt)	2*StdDev (%)	0.15%	0.15%	0.15%	0.15%	0.15%	

Torque (R.H.)		Cal #1 0-1968.5 inlb, by 196.85 inlb increment 19	Cal #2 0-1968.5 inlb, by 196.85 inlb increment 19	Cal #3 0-1968.5 inlb, by 196.85 inlb increment 0.20%	Cal #4 0-1968.5 inlb, by 196.85 inlb increment 0.11%	Averages	2*StdDev(%) of Average Cal Factors n/a
Range	# of spots	-241.7077	-241.8252	-241.7664	-241.7664	-241.7664	
Average Cal Factor (inlb/volt)	2*StdDev (%)	0.20%	0.11%	0.16%	0.16%	0.16%	

Note: The weights used for these calibrations are calibrated every 2 years to a tolerance of 0.01%

Table D.3. Calibration uncertainty for the model drag, shaft thrust, and shaft torque gages for the second resistance and powering test series.

Drag (ahead)						
Range	Cal #1	Cal #2	Cal #3	Cal #4	Cal #5	2*StdDev(%) of Average Cal Factors
# of spots	31	31	31	31	31	0.12%
Average Cal Factor (lb/volt)	-49.8348	-49.8634	-49.8758	-49.7917	-49.8184	-49.8368
2*StdDev (%)	0.42%	0.24%	0.18%	0.38%	0.24%	0.29%

Thrust (ahead)						
Range	Cal #1	Cal #2	Cal #3	Cal #4	Cal #5	Cal #8
# of spots	17	17	0-900 lb, by 100 lb increment	17	17	Averages
Average Cal Factor (lb/volt)	99.9320	99.9149	99.9521	99.8418	99.9064	99.8589
2*StdDev (%)	0.09%	0.11%	0.09%	0.24%	0.16%	0.16%

Torque (R.H.)						
Range	Cal #1	Cal #2	Cal #3	Cal #4	Cal #5	Cal #6
# of spots	19	19	0-1968.5 inlb, by 196.85 inlb increment	19	19	2*StdDev(%) of Average Cal Factors
Average Cal Factor (inlb/volt)	-226.3549	-226.4562	-226.4713	-226.4684	-226.8203	-226.7572
2*StdDev (%)	0.07%	0.06%	0.05%	0.07%	0.04%	0.06%

Note: The weights used for these calibrations are calibrated every 2 years to a tolerance of 0.01%

Table D.4. Model speed measurement uncertainty, model test speed range of 3.5-18 knots,
for the first resistance and powering test series.

3.5 knot data					
exp#	287	# of spots	36	avg	5.919
2*StdDev	0.008	%	0.14%		

6 knot data					
exp#	288	# of spots	26	avg	10.134
2*StdDev	0.012	%	0.12%		

10 knot data					
exp#	257	277	286	298	328
# of spots	24	28	33	21	20
avg	16.891	16.881	16.871	16.878	16.888
2*StdDev	0.007	0.030	0.012	0.010	0.010
%	0.04%	0.18%	0.07%	0.06%	0.06%

16 knot data					
exp#	289	# of spots	24	avg	27.005
2*StdDev	0.042	%	0.15%		

18 knot data					
exp#	263	268	272	273	278
# of spots	20	26	26	23	12
avg	30.379	30.393	30.398	30.395	30.377
2*StdDev	0.013	0.040	0.024	0.037	0.021
%	0.04%	0.13%	0.08%	0.12%	0.07%

total all 18 kn test					
exp#	288	# of spots	5	avg	16.882
2*StdDev	0.014	%	0.08%	avg %	0.08%

Table D.5. Model speed measurement uncertainty, model test speed range of 6-18 knots,
for the second resistance and powering test series.

6 knot data							total all									
exp#	435	442	450	453	456	459	464	463	462	461	446	438	437	434	433	432
# of spots	25	23	30	30	30	30	20	19	19	19	14	14	14	19	19	28
avg	10.165	10.153	10.168	10.161	10.176	10.159	30.416	30.392	30.422	30.426	30.399	30.404	30.421	30.408	30.408	
2*StdDev	0.008	0.024	0.019	0.007	0.025	0.005	0.060	0.024	0.017	0.055	0.040	0.025	0.027	0.019	0.019	
%	0.07%	0.24%	0.19%	0.07%	0.24%	0.05%	0.20%	0.08%	0.07%	0.18%	0.13%	0.08%	0.09%	0.12%	0.06%	
10 knot data							total all									
exp#	436	441	441	441	441	441	441	441	441	441	441	441	441	441	441	441
# of spots	42	32	32	32	32	32	2	2	2	2	2	2	2	2	2	42
avg	16.902	16.908	16.908	16.908	16.908	16.908	16.905	16.905	16.905	16.905	16.905	16.905	16.905	16.905	16.905	
2*StdDev	0.010	0.030	0.030	0.030	0.030	0.030	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	
%	0.06%	0.18%	0.18%	0.18%	0.18%	0.18%	0.12%	0.12%	0.12%	0.12%	0.12%	0.12%	0.12%	0.12%	0.12%	
16 knot data							total all									
exp#	439	440	440	440	440	440	440	440	440	440	440	440	440	440	440	439
# of spots	24	24	24	24	24	24	2	2	2	2	2	2	2	2	2	24
avg	27.044	27.038	27.038	27.038	27.038	27.038	27.041	27.041	27.041	27.041	27.041	27.041	27.041	27.041	27.041	
2*StdDev	0.033	0.047	0.047	0.047	0.047	0.047	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040	
%	0.12%	0.17%	0.17%	0.17%	0.17%	0.17%	0.15%	0.15%	0.15%	0.15%	0.15%	0.15%	0.15%	0.15%	0.15%	
18 knot data							total all									
exp#	432	433	434	437	438	445	446	463	462	461	464	464	465	465	465	432
# of spots	28	26	19	14	14	18	20	19	19	19	19	19	21	20	16	28
avg	30.408	30.404	30.421	30.399	30.426	30.422	30.416	30.392	30.416	30.388	30.395	30.391	30.404	30.404	30.408	
2*StdDev	0.019	0.029	0.021	0.023	0.019	0.060	0.024	0.017	0.055	0.040	0.025	0.027	0.027	0.037	0.027	
%	0.06%	0.09%	0.07%	0.07%	0.07%	0.36%	0.20%	0.08%	0.06%	0.18%	0.13%	0.08%	0.09%	0.09%	0.12%	

Table D.6. Model drag measurement uncertainty, model test speed = 6,10,16,18 knots,
for the first resistance and powering test series.

	6 knots		10 knots	
	10.1268 ft/sec		16.878 ft/sec	
	RT (lbs)** (data spot)	corrected RT (6kn)	RT (lbs)** (data spot)	corr RT (10 kn)
# of spots	43	43	112	112
average	47.482	47.349	133.487	133.423
2*Stdev	0.595	0.544	1.580	1.554
%	1.25	1.15	1.18	1.16
	16 knots		18 knots	
	27.005 ft/sec		30.3804 ft/sec	
	RT (lbs)** (data spot)	corr RT (16 kn)	RT (lbs)** (data spot)	corr RT (18 kn)
# of spots	25	25	26	26
average	320.207	320.837	395.952	396.221
2*Stdev	3.768	3.121	4.410	4.515
%	1.18	0.97	1.11	1.14
Total Average %	1.11			

** each data spot = an average of 2000 samples collected over a
5 second collection time at a rate of 400 samples/sec.

Table D.7. Model drag measurement uncertainty, model test speed = 6,10,16,18 knots,
for the second resistance and powering test series.

	6 knots 10.1268 ft/sec		10 knots 16.878 ft/sec	
	RT (lbs)** (data spot)	corrected RT (6kn)	RT (lbs)** (data spot)	corrected RT (10kn)
# of spots	171	171	38	38
average	47.688	47.359	131.986	131.712
2*Stdev	0.551	0.521	1.300	1.148
%	1.16	1.10	0.98	0.87
	16 knots 27.005 ft/sec		18 knots 30.3804 ft/sec	
	RT (lbs)** (data spot)	corrected RT (16kn)	RT (lbs)** (data spot)	corrected RT (18kn)
# of spots	14	14	62	62
average	313.106	312.790	383.816	383.846
2*Stdev	0.989	0.922	1.771	2.094
%	0.32	0.29	0.5	0.5
Total Average % 0.70				

** each data spot = an average of 2000 samples collected over a
5 second collection time at a rate of 400 samples/sec.

Table D.8. Model thrust, torque, and rpm measurement uncertainty, model test speed=18 knots, for the first resistance and powering test series.

Thrust		Torque		RPM	
18 knot data		18 knot data		18 knot data	
exp#	263	268	272	273	290
# of spots	20	26	26	23	22
2*Stddev (%)	0.758	0.761	0.293	0.467	0.416
				0.364	0.449
				0.919	0.274
				0.285	0.23
				2*Stddev	# tests
					10
					0.50 %

Table D.9. Model thrust, torque, and rpm measurement variation, model test speed=18 knots, for the second resistance and powering test series.

Thrust

18 knot data							average of all 18 kn test							
exp#	432	433	434	437	438	445	446	461	462	463	464	465	# tests	16
# of spots	28	26	19	14	14	18	20	19	19	21	20	20	# tests	12
2*Stddev (%)	1.067	0.758	1.232	0.358	1.091	0.466	0.561	0.354	0.478	0.520	0.404	0.368	2*Stddev	0.64 %

Torque

18 knot data							average of all 18 kn test							
exp#	432	433	434	437	438	445	446	461	462	463	464	465	# tests	16
# of spots	28	26	19	14	14	18	20	19	19	21	20	20	# tests	12
2*Stddev (%)	0.504	0.519	0.258	0.352	1.072	0.442	0.525	0.347	0.422	0.507	0.441	0.337	2*Stddev	0.48 %

RPM

18 knot data							average of all 18 kn test							
exp#	432	433	434	437	438	445	446	461	462	463	464	465	# tests	16
# of spots	28	26	19	14	14	18	20	19	19	21	20	20	# tests	12
2*Stddev (%)	0.225	0.236	0.110	0.164	0.517	0.226	0.252	0.164	0.237	0.235	0.230	0.168	2*Stddev	0.23 %

APPENDIX E :
UNCERTAINTIES OF FULL-SCALE MEASUREMENTS

The relative total (precision + bias) uncertainties of full-scale measurements of the ship speed, propeller rpm, thrust, torque, and shaft horsepower reported for four full-scale trials (USS Boise SSN764, USS Columbus SSN762, USS Charlotte SSN 766, USS Memphis SSN 691) are given below

Reported uncertainties of full-scale measurements

ship	speed	rpm	thrust	torque	SHP
SSN 764	0.6%	1.9%	4.1%	0.3%	1.9%
SSN 762	0.6%	0.5%	4.1%	0.3%	0.6%
SSN 766	0.3%	0.2%	2.2%	0.9%	0.8%
SSN 691	n/a	0.2%	2.2%	1.4%	0.9%

Appreciable variations can be observed in the foregoing uncertainties. Reasonable estimates of these uncertainties are listed below

Uncertainties of full-scale measurements used in analysis

speed	rpm	thrust	torque	SHP
0.6%	0.4%	3.0%	0.9%	0.9%

These estimates of full-scale measurement uncertainties are used in the present analysis.

REFERENCES

- [1] Hugh W. Coleman and W. Glenn Steele, *Experimentation and uncertainty analysis for engineers*, 1989, John Wiley and Sons.

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